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PROCEEDINGS

PART II

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SYMPOSIUM ON EFFECT OF TEMPERATURE UPON THE PROPERTIES OF METALS[1]

A REVIEW OF THE PRESENT STATE OF KNOWLEDGE OF THE PROPERTIES OF METALS AT VARIOUS TEMPERATURES AND A DISCUSSION OF THE NECESSITY FOR PROMOTING FURTHER KNOWLEDGE

FOREWORD

Greater economy and security in central-station development and in oil-refinery operations require the designing engineer to have an accurate knowledge of the properties of metals under stress at high temperatures. Lack of this knowledge gives rise to a critical situation and it is therefore timely that The American Society of Mechanical Engineers and the American Society for Testing Materials are joining in the presentation of the four papers that introduce this Symposium. These papers set forth the importance of having information available, discuss the difficulty of comparing tests that have already been made on metals at high temperatures, and review the knowledge now existing in regard to the properties of metals at high and low temperatures.

Some such topical discussion as will result from the presentation of these papers at Cleveland would sooner or later have been forced by the necessity for a cooperative attack on the problem of securing data to provide for the actual construction of central stations operating at high temperatures. This joint session, however, is the direct outcome of the activity of Sub-Committee No. 3 on Steel Flanges, Sectional Committee on the Standardization of Pipe Flanges and Fittings, organized under the procedure of the American Engineering Standards Committee. Interest in the subject was stimulated by the discussion on the paper presented at the 1922 Annual Meeting of the A.S.M.E. by G. A. Orrok and W. S. Morrison on the Commercial Economy of High Pressure and Superheat in the Central Station, and by the papers by Frederick N. Bushnell and Charles H. Merz before the meeting of the National Electric Light Association in June, 1923.

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[1] Held at a Joint Meeting of The American Society of Mechanical Engineers and the American Society for Testing Materials, May 29, 1924, Cleveland, Ohio.

This joint session at the Cleveland Meeting of the A.S.M.E. is but the first step, and it is the earnest hope of the two Societies that out of the discussion of the papers in question there will evolve a definite program of cooperative standardization and research upon which the commercial uses of metals at high and low temperatures may be based. There is much work that may immediately be accomplished, such as:

1. Accumulation of existing unpublished data covering satisfactory and unsatisfactory service of various metals in different fields.
2. Standardizing procedure for testing materials at high and low temperatures. This should preferably include new comparative tests of metals by the principal methods now in use in various laboratories and likewise, a critical examination of data already published.
3. Outlining new research work to be done. The first and most important materials to be investigated are considered to be carbon and alloy steels, so-called "heat-resisting" alloys consisting of various combinations of nickel, chromium, iron, tungsten, molybdenum, etc., and trimming materials (chiefly alloys of nickel and copper) for valves and equipment intended for high-temperature service in power stations, oil refineries, etc.

To carry forward these three projects will require the wholehearted cooperation of the technical and industrial organizations interested.

The Symposium was arranged by the following committee, which acted in an advisory capacity to the Committees on Papers and Publications of the two Societies:

V. T. Malcolm, *Chairman*
H. J. French
W. F. Graham
R. S. MacPherran
L. W. Spring
A. E. White

The two Societies take this opportunity of expressing their appreciation of the services of this committee.

INDUSTRIAL APPLICATIONS OF METALS AT VARIOUS TEMPERATURES

BY L. W. SPRING[1]

About one hundred and fifty years ago James Watt improved Newcomen's "atmospheric" steam engine and went to the then "enormous" steam pressure of ten pounds per square inch, utilizing in addition the expansive force of steam as well as its direct pressure. From that time till now, though quite slowly, steam pressures have gone up and up, through 50, 100, 150, 200 and 250 lb. per sq. in. each with its increasing temperature, until of late years pressures of 350 lb. per sq. in. are more or less common. Though the superheating of steam before using was suggested by Watt it was not actually tried out by him and its use did not become at all common until within the last twenty years. In superheat practice the steam is given an additional 150 to 300° F. (85 to 170° C.) of temperature, obtained, of course, by passing the steam from contact with the water in the boiler into another chamber, or through superheater pipes. Here it is converted by the further heating into "dry" steam with the additional heat mentioned, having then a total temperature of from 550 to 750° F. (288 to 400° C.).

While the increases in pressures and temperatures during the approximately one-hundred-and-fifty-year period mentioned have been quite gradual, at the present time a seemingly rather drastic change is taking place which at first thought may appear to some to be very sudden, and possibly unwise, though it must be admitted that technical and mechanical talent have made wonderful strides within the last two decades. This change is the very decided increase in working steam pressures, which almost everywhere is occupying the thought of power plant designing engineers and which, in some cases, is already being translated into actual plant installation. Regular working pressures of 600 lb. per sq. in. are being or shortly will be used in two or three plants which are looking toward the greatest possible efficiency to be obtained with safety. Undoubtedly, increases in working pressures are not to stop here. Three or four power plant designers in this country already have arranged to try out, in a commercial way, in small units, steam at 1200 lb. working pressure. These have as antecedents a German experimental plant which operated at 900 lb.

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[1] Chief Chemist and Metallurgist, Crane Co., Chicago.

pressure for a period of nine months and a plant in Sweden, which, though built for 1500 lb., is now operating at 900 lb. per sq. in. In one installation in England the full critical steam pressure of 3200 lb. per sq. in. is to be tried shortly.

When generated freely from water, that is without pressure, steam occupies approximately seventeen hundred times the volume of the water it came from and has a specific gravity or density of about 0.0006. At the critical pressure of 3200 lb. per sq. in., however, and under a temperature of at least 706° F. (375° C.), it occupies only the equivalent of the volume of water from which it was generated and has, therefore, a specific gravity of approximately 1. In other words, under these conditions it has the same specific gravity as the water in the boiler and it is possible that the steam may be in and through the water or even below it in the boiler, since the two have the same density. The speculative possibilities and the promises of largely increased efficiencies by operating at 3200 lb. pressure and 750° F. (400° C.) are very interesting and have been quite thoroughly discussed elsewhere.

Without dwelling longer on the subject of pressures, which have been referred to mainly to indicate the rather extreme tendency toward higher efficiencies and therefore toward new designs and probably new materials in steam power practice, we will pass to the matter of temperatures.

As told above, present-day superheated steam practice has developed rapidly during the past twenty years with the result that a large number of power plants now use total operating temperatures of 550 to 750° F. (288 to 400° C.) A superheat of 315° F., that is, 750° F. (400° C.) total temperature, has been and is yet considered the tentative top limit of temperature for high-pressure power plant work. The reason for this is that metals which at present are available for steam generating purposes undergo considerable losses in strength as their temperatures rise above 600° F. (315° C.) Just where the point of recession begins and exactly where the curves of tensile strength, elastic limit, elongation and reduction of area lie with temperature increases, are matters upon which metallurgists are not yet quite fully agreed. Safety requires that we go slow in increasing operating temperatures above the 750° F. (400° C.) total temperature. How much this tentative maximum can be raised with safety eventually will depend in great measure upon agreement of results of metallurgists who are determining the strengths of materials to be used for power plant purposes and also upon more satisfactory materials which probably will be devised. While working pressures are being increased now by leaps and bounds, because these can be taken care of by increase in metal thickness, it is probable that increases of working temperatures will be much more slowly and cautiously made.

There is a second extensive use of this class of materials at high temperatures, and here working temperatures have considerably exceeded the 750° F. (400° C.) mark. This is the application of these metals: cast steel, malleable iron, and other boiler, piping and valve materials, to the oil refining industry. In the early days of petroleum refining it was chiefly the "coal oil" or kerosene which was utilized. There were at that time no internal combustion engines with their demand for the more volatile gasoline. Likewise there was little demand for petroleum lubricants, animal oils being considered the proper lubricants for machinery. With the expanding use of the automobile and the tractor, the demand for gasoline and the volatile portion of petroleum has outrun their production through straight distillation methods. Hence there have been made extensive efforts through high temperature or combined temperature and pressure "cracking" to increase the production of gasoline or a serviceable equivalent by such artificial breaking up of the less valuable, heavier petroleum oils. Without going into the history of their development it can be said that there are now somewhere around fifteen or twenty recognized "cracking" processes. These vary considerably in type of apparatus used and in the application of heat, the taking off, separation, and condensation of the vapors formed, as well as in pressures and temperatures used. In general, it may be said that the pressures are comparatively low, though there seems to be a trend toward the use of higher ones. The majority of these processes use pressures of around 100 lb. per sq. in. with temperatures of from 750 to 850° F. (400 to 450° C.). Three or four use 350 lb. pressure and 900° F. (480° C.), while one uses as high as 600 lb. pressure and 900° F. (480° C.). Pressures in the latter process probably surge as high as 750 lb. per sq. in., and temperatures may go as high as 950° F. (510° C.). Two such processes are utilizing as high as 1000° F. (540° C.) of temperature, with, however, only 350 lb. of pressure. While, apparently, there has been little or no trouble as to materials standing up so far as actual strength is concerned, even at these temperatures, anxiety naturally exists in the minds of both user and producer over consequences should any material containing flaws get into service. Furthermore, failures might occur through corrosion, breaking of parts under pipe strains, etc. Any failure is serious since the uncondensed vapors from the cracking stills are extremely inflammable and explosive.

As will be shown by the contributions of others to this program, losses in strength of cast steel at such high cracking temperatures as

900 and 1000° F. (480 to 540° C.) are rather great, considerably more so than at 750° F. (400° C.), the tentative top point for superheated steam service. However, under existing pressures and other service conditions, cast steel is serving well. Whether much will be gained by further increase in cracking temperatures and what further pressure increases may be made remains for the future to tell.

There are certain non-ferrous metals which are made use of in equipment for power plants and oil refineries. These are the metals or alloys of which steam turbine blades, valve seats, and sometimes other parts of valves are made. In general, valve-seat alloys contain as a base considerable percentages of nickel and copper. Under increased temperatures some of these alloys do not suffer more than cast steel, so far as strength is concerned. In addition to good strength under working conditions such alloys must have sufficient hardness to resist the cutting action of steam, scale or grit, for, to be satisfactory, valve seats must remain tight. Seating metals must have approximately the same coefficient of expansion under heat as that of the valve body and disk metal, and they should be as non-corrosive as possible, for corrosion also is an enemy to valve tightness. While considerable research is constantly going on, the ideal valve-seating material for high-pressure, high-temperature steam probably has not been found, and, certainly, the proper seating metal for oil-cracking vapor service is yet a matter of doubt.

While in the ferrous alloys the plain carbon steels have given satisfactory service so far and undoubtedly can be used safely at somewhat higher temperatures than are considered wise at present, it may be that alloy steels eventually will be found desirable.

Such alloys as chrome-nickel, chrome-iron-nickel, and others which are often used for carbonizing boxes, annealing pots, supports for articles in enameling ovens, floors and arches of furnaces, where temperatures of from 1600 to 2000° F. (870 to 1100° C.) prevail, are hardly within the scope of this paper. It is possible, however, that these indicate the trend toward other materials which may be necessary to keep pace with the demand for higher operating pressures and temperatures in various industrial applications.

METHODS OF TESTING AT VARIOUS TEMPERATURES AND THEIR LIMITATIONS

By V. T. Malcolm[1]

Introduction

In the design of apparatus for use at temperatures either above or below normal, it is of importance that the designer be familiar with the physical characteristics of the metals or alloys specified at the temperature to which they will be subjected in service. As many processes require the use of metals at temperatures other than normal, the degree of success of a metal or alloy must be measured by its stability under such working conditions. As a matter of fact, most failures at temperatures other than normal are due not to the quality of the metal or alloy but to the improper application of certain metals in connection with work for which they are entirely unsuited. For use at other than normal temperatures a careful study must be made of an alloy's characteristics, for with the advent of the central power station and oil refinery operating at great pressure and high temperature, failure of material in service is likely to be disastrous both to property and life.

At the Power Session(**190**)[2] of the annual meeting of the American Society of Mechanical Engineers held December 7, 1922, at New York City, a statement was made that power plant equipment had kept pace with the demand, except information regarding the properties of metals at elevated temperatures. Again at the Annual Convention(**195**) of the National Electric Light Association held June 4, 1923, New York City, it was claimed that while higher pressures were assured, higher temperatures must be provided for in metallurgy. In *Mechanical Engineering*(**211**), March, 1924, a résumé of power plant progress is given, and the author calls attention to the fact that the use of temperatures above 750° F. (400° C.) has not been contemplated owing to the lack of reliable information.

The importance of these statements to the mechanical engineer is profound, as he is directly responsible for the safety of the structures he designs, and he is probably unwilling to take for granted that a metal is suitable for other than normal temperatures without being convinced that tests have been carried out in a correct manner.

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[1] Metallurgist, The Chapman Valve Manufacturing Co., Indian Orchard, Mass.

[2] The boldface numbers in parentheses refer to the papers of the Bibliography appended hereto, page 128.

The testing of metals at temperatures other than normal is probably one of the most vital fields of engineering research to-day and will in the near future be one of the most actively exploited fields of metallurgy in the search of alloys, both ferrous and non-ferrous, to withstand temperatures other than normal. A most cursory examination of scientific and technical literature will convince anyone of the extent of scientific interest in this subject, and we believe it is one of the most serious problems confronting industries to-day.

The ultimate aim of all temperature tests should be to devise a comprehensive series of tests to which standard specimens of metals or alloys may be subjected and by which the relative physical properties of these metals may be predicted for certain service conditions. At this time anyone who undertakes a survey of the literature on the temperature problem is certain to be overwhelmed by the different types of furnaces, extensometers, strain gages, thermocouple location, etc., that have been used by the various investigators, and on the other hand numerous curves and data are shown, which are comparatively worthless to the designing engineer, unless the method of making tests and reaching thermal equilibrium are shown. Therefore, the problems at hand are of such importance that it becomes necessary to give statements on the apparatus used, method of testing, and manner of reaching thermal equilibrium.

It is with this idea in mind that an attempt has been made to review part of the literature with reference to tests of metals at various temperatures by investigators who are thoroughly familiar with their work. and it is hoped in this way to reach some definite plan by which the work of these men may be correlated and standardized apparatus, method of testing, etc., developed for use in all future tests.

HISTORICAL

In reviewing the literature on the testing of metals at various temperatures, it is well to go back to the beginning and carry the work forward to the present time in order to show the remarkable progress that has been made in methods of test in this branch of engineering research.

As early as 1828 Tremery and Proirier Saint-Brice(1) carried out a series of experiments on the tensile strength of wrought iron. In 1837 Sir William Fairbairn(2) made a number of experiments on cast iron at various temperatures. In 1837 research was carried on by a Committee, of The Franklin Institute(3), on the Effect of Temperature on Boiler Plate. In 1856 Fairbairn(4) carried out a series of experiments on rolled iron at various temperatures. In 1860 David Kirkaldy(5) of Glasgow, Scotland, carried out a number of interesting experiments on the value of iron and steel at various temperatures, especially investigating the action of frost upon the metals. William Brockbank(7) describes some very interesting experiments in determining the effect of cold upon cast iron. In 1863 a series of tests was conducted by the Royal Technological Institute of Stockholm(6), on the properties of irons and steels at various temperatures. In 1871 Peter Spence(8) carried out a number of investigations with cast iron at low temperatures. Jouroffsky(12) of St. Petersburg in 1879 conducted a number of tests on rails at low temperatures.

Between 1885 and 1905 a great deal of attention was given the subject of testing metals at various temperatures by such well-known investigators as Rosenhain and Humfrey(74, 93), LeChatelier(39), Martens(18), Bach(44, 50), Unwin(16), Hopkinson and Rogers(55), Rudeloff(20, 36, 64), Stribeck(48, 52), Howard(17), Charpy(21, 25), Carpenter(24), and Hadfield(54) and quite numerous articles appeared in the German and British engineering literature. Very little work was done in the United States during this period with the exception of the work of Howard.

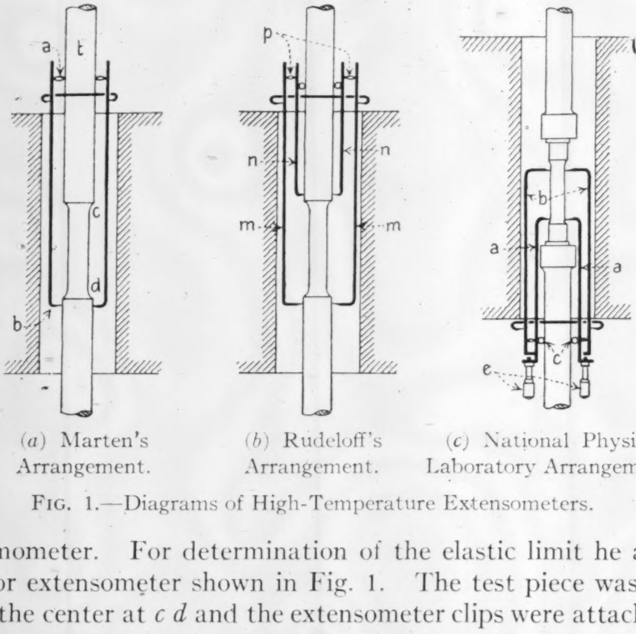
The modern line of investigation was begun about 1912 and is still being carried on to the present day by such investigators as Huntington(85), Bengough(82), Hansen(101), Dewrance(98), Aitchison(123), Lea(187), Dickenson(173), Dupuy(150), in England and France, and in this country by such men as Meyers(128), Spring(83, 216), Jeffries(127), Sykes(163), Merica(168), McNiff(144), French(153, 179), Spooner(162), MacPherran(158), Langenberg(200, 201), Epps and Jones(116), Perrine and Spencer(104), Priester and Harder(206), White and Upthegrove(147), Speller(215), d'Arcambal(148) and the author(188, 189, 203, 212).

EARLY METHODS OF TESTING

The old methods used for testing metals at various temperatures consisted of heating a specimen in a furnace or forge or freezing it in some liquid medium, transferring it to a testing machine and quickly conducting the test at normal temperature, allowing for loss or gain of heat in transferring test bars and in conducting the test. In some cases the temperature was merely judged by the oxide film on the specimen and in other cases by the use of thermometers. These methods were of course very crude and the results unreliable, but as this was before the day of our modern equipment the tests served their purposes.

In 1888 a most extensive series of tests was made by Howard(17) at the Watertown Arsenal, and as this was also before the day of the electric furnace and the pyrometer the specimens were heated by a series of Bunsen gas burners and the temperature estimated from the coefficient of expansion of the heated specimen. No temperature correction for the coefficient of expansion was used. These tests received and still receive quite an amount of favorable comment.

In 1890 Martens(18) published his investigations on the tensile properties of iron, steel and copper at elevated temperatures. He used a bath of paraffin for temperatures up to 400° F. (200° C.) and a bath of lead or lead-tin alloy for temperatures from 400 to 1100° F. (200 to 600° C.) The gas jets were located on the sides in conjunction with a vertical testing machine. For measuring temperatures he used in the former case a mercury thermometer and in the latter case an air thermometer. For determination of the elastic limit he adapted his mirror extensometer shown in Fig. 1. The test piece was turned down in the center at *c d* and the extensometer clips were attached at *b* on the lower enlarged end and were carried out of the furnace, for the attachment of the measuring rhombs *a*. The extension, therefore, was measured on the length *a b* and correction was made for the extension of the enlarged ends, in order to obtain the extension of the gage length, *c d*.



(*a*) Marten's Arrangement.
(*b*) Rudeloff's Arrangement.
(*c*) National Physical Laboratory Arrangement.

FIG. 1.—Diagrams of High-Temperature Extensometers.

Unwin(16) in 1889 published results of tests of metals at elevated temperatures. These tests were carried out by heating the specimens in an oil bath from below by gas burners, the whole apparatus being placed between the jaws of a testing machine as shown in Fig. 2. Thermometers were used to measure the temperature. Charpy(25) in 1896 also used a bath with burners located below. LeChatelier(39) used a horizontal testing machine with gas jets located above. Batson(80) used steam coils in the testing of 50-ft. lengths of copper wire up to temperatures of 140° F. (60° C.). Stribeck(48, 52) used a cylindrical oven, electrically heated, through which the bar passed. Other investigators used methods more or less similar, the main features

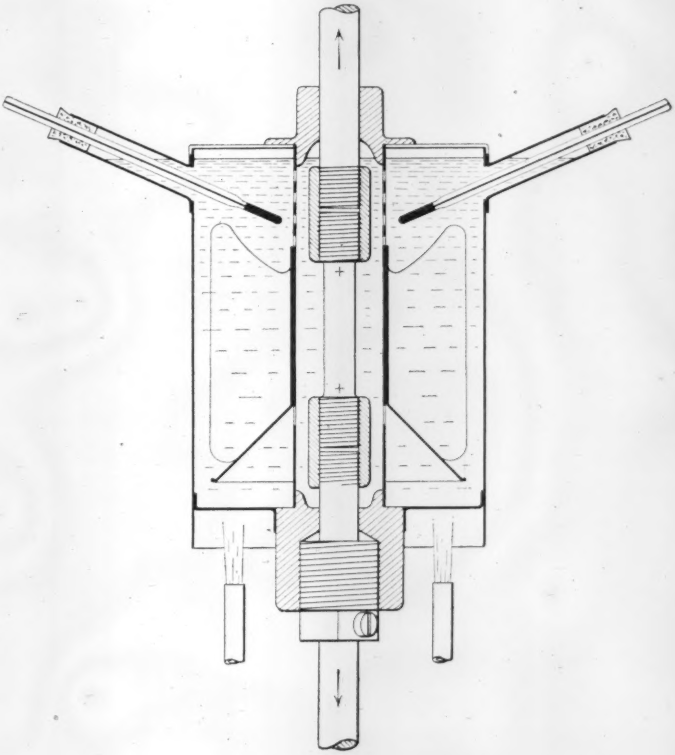


FIG. 2.—Diagram of Testing Apparatus Used by Unwin.

being air, gas or liquid baths heated by blast lamps, Bunsen burners, or electric current, and in the case of low temperature a freezing solution.

In nearly all the early investigations we find that temperatures were taken at points distant from the test specimen itself, the assumption being that temperature of bath and test bar must be alike.

It is therefore our conclusion that most of the early investigations can be only approximate determinations at best.

MODERN METHODS OF TENSION TESTING

During the past ten years methods of furnace construction, location of the thermocouple, calibration of pyrometer, and the general checking up of the work in hand has received close attention and great accuracy has been attained, so that at this time conclusive results have been arrived at and industrial applications certainly may be based on these findings.

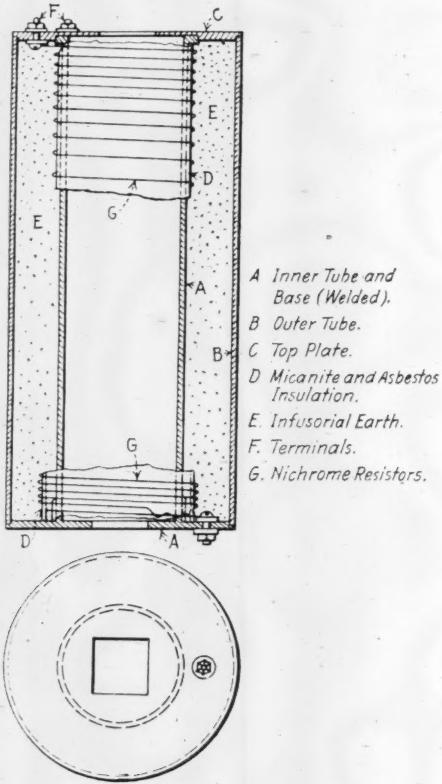

F
C
E
D
G
E
A
B
G
D
A
A Inner Tube and Base (Welded).
B Outer Tube.
C Top Plate.
D Micanite and Asbestos Insulation.
E. Infusorial Earth.
F. Terminals.
G. Nichrome Resistors.

FIG. 3.—Electric Furnace Used by French in High-Temperature Tests.

The apparatus and methods of test of some of the more prominent investigators during the past ten years will be described in detail. Attention will first be devoted to tension tests, after which reference will be made to other tests of metals at various temperatures.

H. J. FRENCH(153, 179)

Furnace.—The test specimens are heated by means of an electric furnace shown in Fig. 3. Two spiral resisters in series are used: one covers the entire length of the inner tube (11 in.) and the other is concentrated at the ends, the two requiring about 80 ft. of No. 22 nichrome wire. Yokes and the greater part of the test bar and rods are contained in the heating chamber, which is 11 in. long. The furnace is operated on either 110 or 220-volt direct current, close regulation being obtained by a variable resistance in series in the circuit.

Proportional Limit Apparatus.—The apparatus used in the determination of the limit of proportionality at various temperatures, illustrated in Fig. 4, consists primarily of two aluminum-alloy frames each rigidly fastened to a quenched-and-tempered steel yoke by two annealed low-carbon steel rods. The specimen passes freely through holes in the base of each of the frames. Yokes are clamped to the specimen by three quenched-and-tempered high-speed steel screws, while the spreading of the former is overcome by the long screw. The flanges on the upper frame are so arranged that dial micrometers for indicating deformation may readily be securely fastened to them, while those of the lower frame are capped with polished steel plates in order to give a smooth bearing surface to the plungers of the dials.

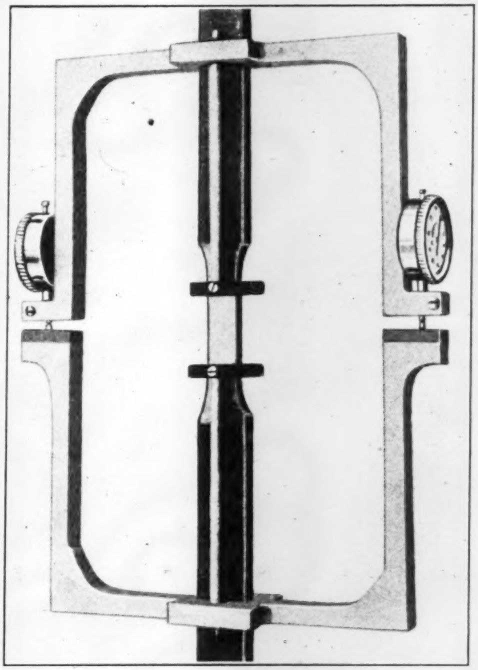


FIG. 4.—Apparatus Used by French for Determining Proportional Limit.

The smallest division on the instruments used is equal to 0.001 in., but estimated readings to the nearest 0.0001 in. are readily obtained.

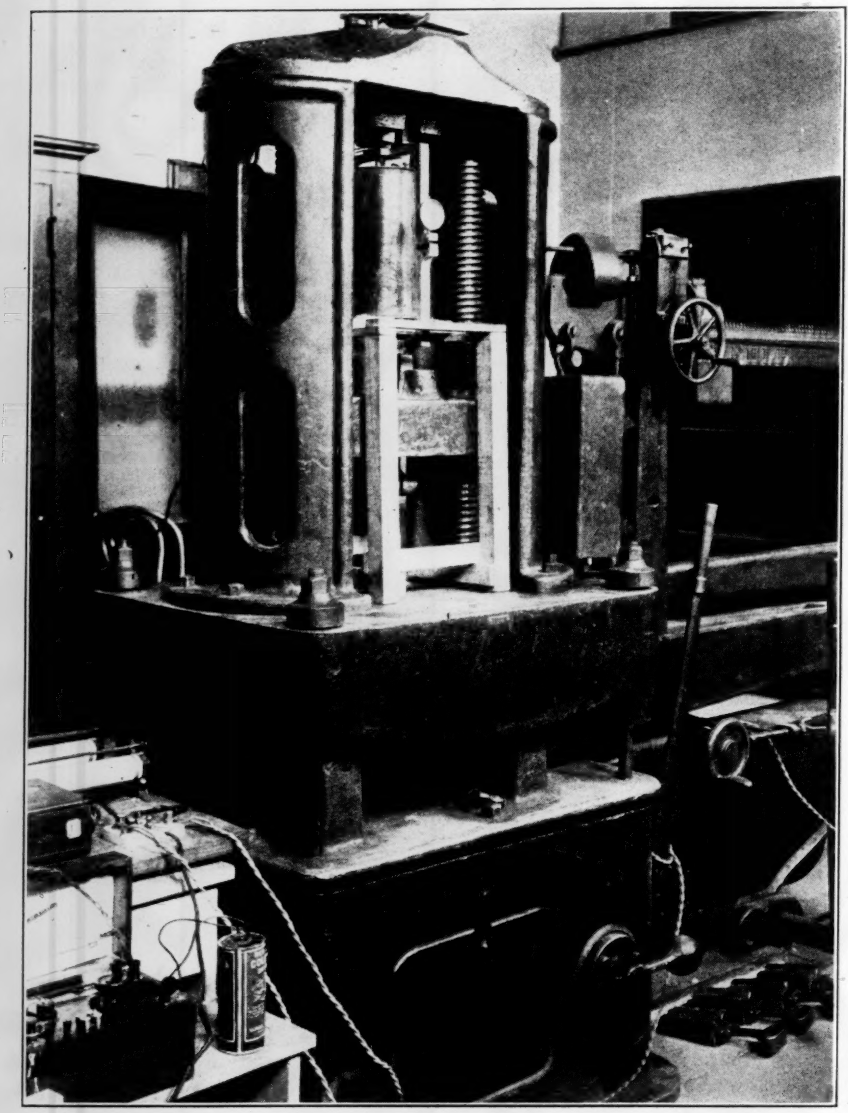


FIG. 5.—Assembled Apparatus Used by French for Determining the Tensile Properties of Metals at High Temperatures.

When stress is applied to the specimen, one-half the algebraic sum of the deformation recorded by the two dials represents the deformation of the specimen, which is centrally located with respect to the entire apparatus.

Test Procedure.—The method of setting up the apparatus together with the procedure followed in actually carrying out the tests is substantially as follows: A specimen is marked on the surface with a double-pointed center punch leaving marks 2 in. apart. The yokes are attached to the specimen by setting the single screw into the impressions. Then by lightly tapping the opposite side of the yoke containing the two screws, a light impression of their exact location on the test bar is obtained. These points are then enlarged by use of the double-pointed center punch, and the yokes carrying rods and frames are firmly attached to the test piece. Bolts holding the upper frame to the two rods are next taken off and the upper frame removed.

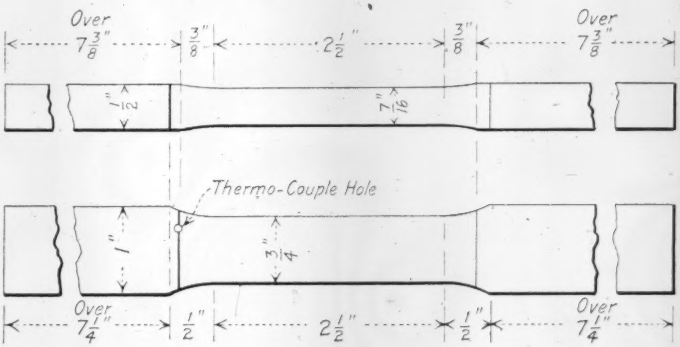


FIG. 6.—Form and Dimensions of Test Specimen Used by French.

The specimen is then passed up through the furnace until the rods appear above the top, when the upper frame is again fastened to the rods After the furnace is placed on the stand and the specimen is in the jaws of the testing machine the dials are attached to frame and adjusted to zero. The completely assembled apparatus is shown in Fig. 5.

When thermal equilibrium at the desired temperature is reached, an initial load of about 1500 lb. is applied and the dials read or, as a matter of convenience, set at 17.2. Readings are then taken at increments of 500 or 1000 lb. actual load until the proportional limit is passed. The dials are then removed and the specimen is broken in the usual manner with a low rate of extension which approximates the intermittent increases of stress applied during determination of the limit of proportionality. Tests at each temperature are made in duplicate or triplicate and the proportional limit is obtained from the stress-strain diagram.

The temperature is measured by a No. 22 standardized chromel-alumel couple connected to a Leeds and Northrup portable potentiometer. The end of the couple is inserted directly into a small hole drilled in the specimen at the fillet, its exact location being shown in Fig. 6.

Thermal Equilibrium.—In order to obtain reliable and satisfactory results with the method described in the preceding paragraphs, thermal equilibrium must be reached prior to the start of the loading and maintained during the actual 8 to 15 minutes during which the test is being carried out. The adjustable resistance in series in the electrical circuit makes current adjustment possible, so that the loss of heat from the heating unit, ends of test specimen and auxiliary apparatus by radiation, convection, and conduction balances the energy added to this entire system. The effect of temperature variations may be large unless care is taken to allow sufficient time for the specimen to become uniformly heated throughout after the potentiometer has once indicated the desired temperature. The dial readings will assist in determining when equilibrium has been reached and is being maintained.

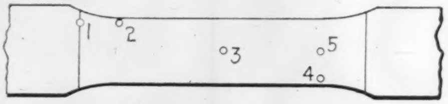


FIG. 7.—Temperatures at Various Parts of Test Specimen.

Desired Temperature		Temperature of Specimen at Points Indicated										Time after Couple No. 1 First Reached Desired Temperature, minutes	Average Temperature of Couples Nos. 2, 3, 4, and 5		Maximum Temperature Variation	
		Point No. 1		Point No. 2		Point No. 3		Point No. 4		Point No. 5						
deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.		deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.
329	165	329	165	343	173	333	167	316	158	329	165	15	299	166	27	15
608	320	608	320	621	327	621	327	590	310	612	322	0	580	322	31	17
		617	325	633	334	633	334	608	320	644	329	5	592	329	25	14
		617	325	637	336	633	334	604	318	630	332	20	594	330	29	16
752	400	756	402	779	415	774	412	739	393	756	402	10	729	405	40	22
		756	402	779	415	774	412	739	393	756	402	20	729	405	40	22

Temperature determinations under actual test conditions, made by placing thermocouples in holes located at various points in the specimen carrying the entire auxiliary apparatus, show that the position chosen for the single thermocouple (in the fillet) is representative of about the mean gradient throughout the gage length, where the temperature gradually decreased from top to bottom. Fig. 7 shows a partial reproduction of these variations, which are within 45° F. (30° C.). It is the greatest in the upper temperature ranges under consideration, and does not exceed 36° F. (20° C.) at the lower temperature used. However, as the thermocouple, specimen with auxiliary apparatus, and furnace are in the same relative position in each test, the results obtained at various temperatures throughout the range, 70 to 870° F. (20 to 465° C.), are comparable.

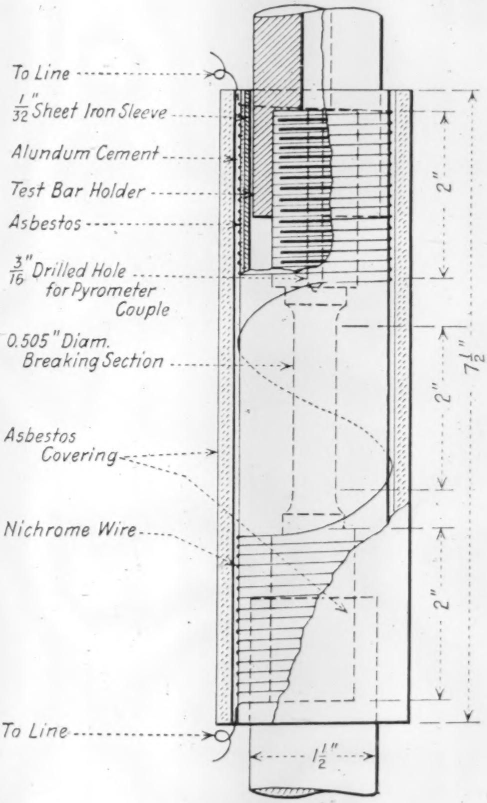

To Line
$\frac{1}{32}$" Sheet Iron Sleeve
Alundum Cement
Test Bar Holder
Asbestos
$\frac{3}{16}$" Drilled Hole for Pyrometer Couple
0.505" Diam. Breaking Section
Asbestos Covering
Nichrome Wire
To Line
2"
2"
2"
7½"
1½"

FIG. 8.—Heating Coil and Test Specimen Used by Bregowsky and Spring.

I. M. BREGOWSKY AND L. W. SPRING (83, 216)

Furnace and Testing Apparatus.—The heating apparatus consists of a $7\frac{1}{2}$ by $1\frac{9}{16}$-in. sleeve of $\frac{1}{32}$-in. sheet iron wrapped with one layer of $\frac{1}{16}$-in. sheet asbestos for insulation, and wound with twenty turns on each end with No. 18 or No. 20 chromel wire, leaving a gap of 3 in. in the middle, except for the approximate one-half turn connection between the end windings. The wire is plastered thinly with alundum cement to prevent excessive oxidation at high temperatures. Outside layers of sheet asbestos, shrunk on, insulate the wires and retain the heat. The coil, test bar and hole drilled in it for the thermocouple are illustrated in Fig. 8. Test bars are turned to 0.505 in. in diameter over breaking section and the ends are threaded to fit the self-centering holders of the testing machine. In the top end of the bar a $\frac{3}{16}$-in. hole is drilled axially to within about $\frac{3}{8}$ in. of the turned-down breaking section. In testing, the coil is suspended from the upper holder. The test bar, heating coil and self-centering holders into which the threaded ends of test bars screw are heat-insulated from the testing machine by $\frac{1}{2}$-in. pads of asbestos, bolted between steel flanges which form parts of the self-centering holders. The general assembly of the apparatus showing insulating flanges, heating coil, extensometer and pyrometer is given in Fig. 9.

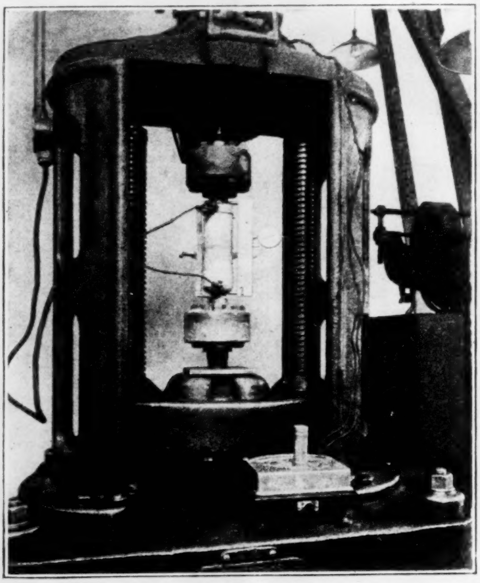


FIG. 9.—Testing Machine Used by Bregowsky and Spring with Test Specimen, Heating Coil and Temperature-Measuring Apparatus in Place.

In the hole in the top end of the bar a thermocouple is inserted, which gives the temperature inside the bar very near the turned-down breaking section. By careful regulation, any desired temperature between 70 and 1200° F. (21 and 650° C.) can be obtained in 20 minutes to 1½ hours and held without more than a few degrees fluctuation. Readings for proportional limit and yield point with the aid of an extensometer attached to the bar holders and breaking the bar (all of which requires four or five minutes) are accomplished within a few degrees of the desired temperature. Temperatures are taken with chromel-alumel couples, carefully standardized against the freezing points of chemically pure tin, zinc and aluminum. Measurements were read on a millivoltmeter.

On various occasions tests were made to determine variation of temperature of test specimens at several internal and external points, using for this purpose specimens drilled axially nearly to the lower end. The thermocouple inserted in the drilled hole was raised or lowered from time to time and readings were taken at various locations inside the bar. When using coils wound over their full length it was found practically impossible to avoid a higher temperature in the center or breaking section of the test bar than at the ends. Part of this variation is attributed to conduction of heat away from the ends of the test bar through the bar holders. Therefore, coils were developed wound on the ends only, and by throwing all the heat upon the ends of the test bar and none along its middle or heating section a quite uniform temperature in the breaking section and adjacent parts was obtained, the variations not exceeding 35° F. at 1200° F. (20°C. at 650° C.).

Tests were made to determine the accuracy of taking temperatures on the surface of the bar, by strapping the tip of another thermocouple to the outside of the drilled test bar at the middle of the breaking section and taking comparative readings after thermal equilibrium had been attained. Of course, these tests showed that temperature readings taken at the surface are somewhat higher than readings taken inside and it is believed that an "outside" thermocouple gets direct radiant heat from the heating coil and therefore registers higher. Moreover, even without direct radiant heat and assuming that the thermocouple registers the temperature of the outer fibers of the bar perfectly, the outer fibers naturally have a higher temperature than the center of the bar, because the heat goes from the surface toward the center.

G. C. PRIESTER AND O. E. HARDER(206)

In order to make tests at elevated temperatures a special apparatus as shown in Fig. 10 was developed. The temperature of the specimen is measured by a carefully calibrated thermocouple, the hot junction of which is clamped in contact with the lower shoulder of the specimen.

The specimen is gradually heated to the desired temperature by means of an electric furnace and is held at this temperature for 30 minutes to establish thermal equilibrium. Under these conditions it is believed that any heat changes that take place during the heating of the specimen are negligible. It is believed that there can be no question about the accuracy of the temperature measurements made in this way.

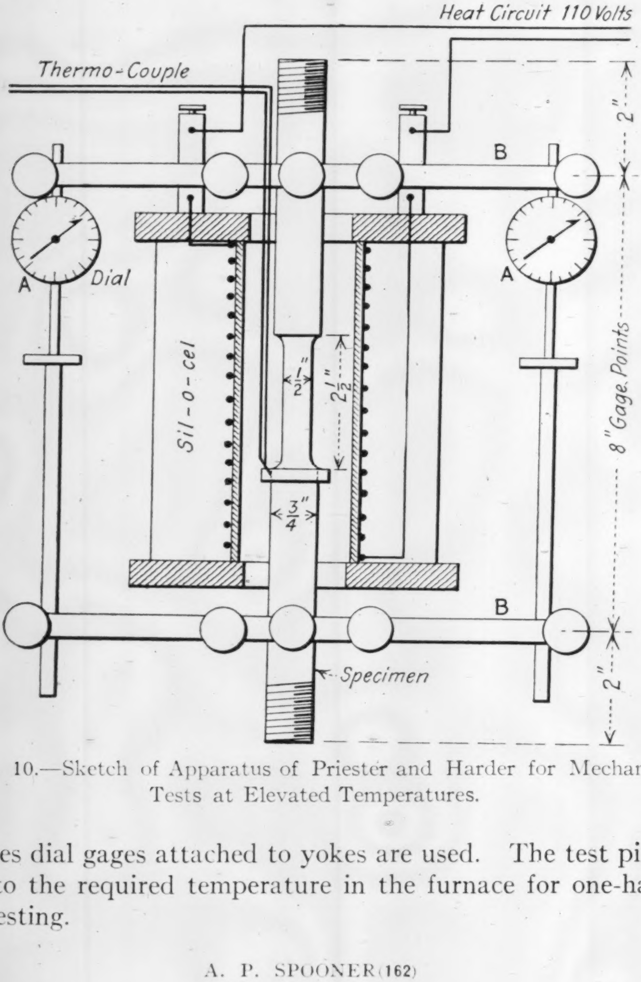


FIG. 10.—Sketch of Apparatus of Priester and Harder for Mechanical Tests at Elevated Temperatures.

Ames dial gages attached to yokes are used. The test pieces are heated to the required temperature in the furnace for one-half hour before testing.

A. P. SPOONER (162)

Specimens are heated in a circular electric furnace, with a thermocouple inserted against the middle of the pull section and connected with a Leeds and Northrup recording pyrometer. The thermocouple is wired to the necked-down section of the specimen and asbestos packing used to close the ends of the furnace tube, which is 1½ in. in diameter. All specimens were held at the testing temperature for 30 minutes before the load was applied. The apparatus is illustrated in Fig. 11.

The specimens are pulled in a 100,000-lb. Emery testing machine. The yield point is determined by the drop of the beam and occasionally checked up with the dividers.

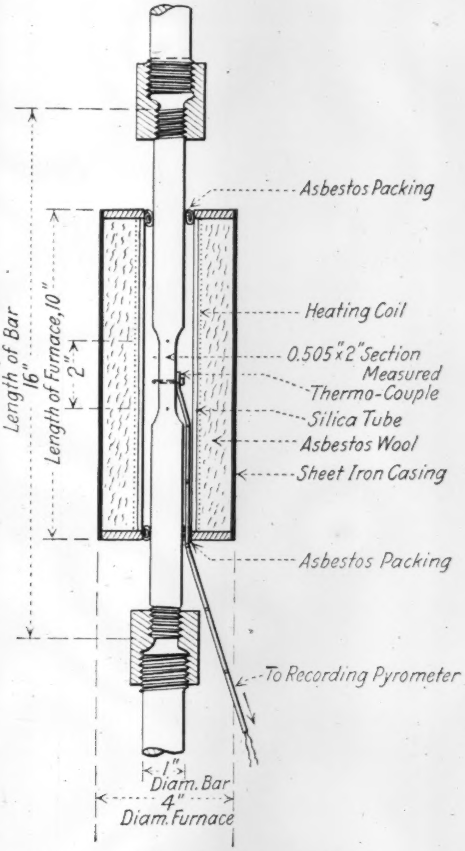

Asbestos Packing
Heating Coil
0.505"x2" Section Measured
Thermo-Couple
Silica Tube
Asbestos Wool
Sheet Iron Casing
Asbestos Packing
To Recording Pyrometer
Length of Bar 16"
Length of Furnace, 10"
2"
1" Diam. Bar
4" Diam. Furnace

FIG. 11.—Arrangement of Test Specimen in Furnace used by Spooner.

An interesting feature to be noted in the tests reported by Spooner is the fracture of the broken test bars at the different temperatures. The usual commercial, structural and carbon steel fractures look very much alike, but with the addition of certain percentages of nickel, chromium and tungsten the colors of the fractured bars change considerably.

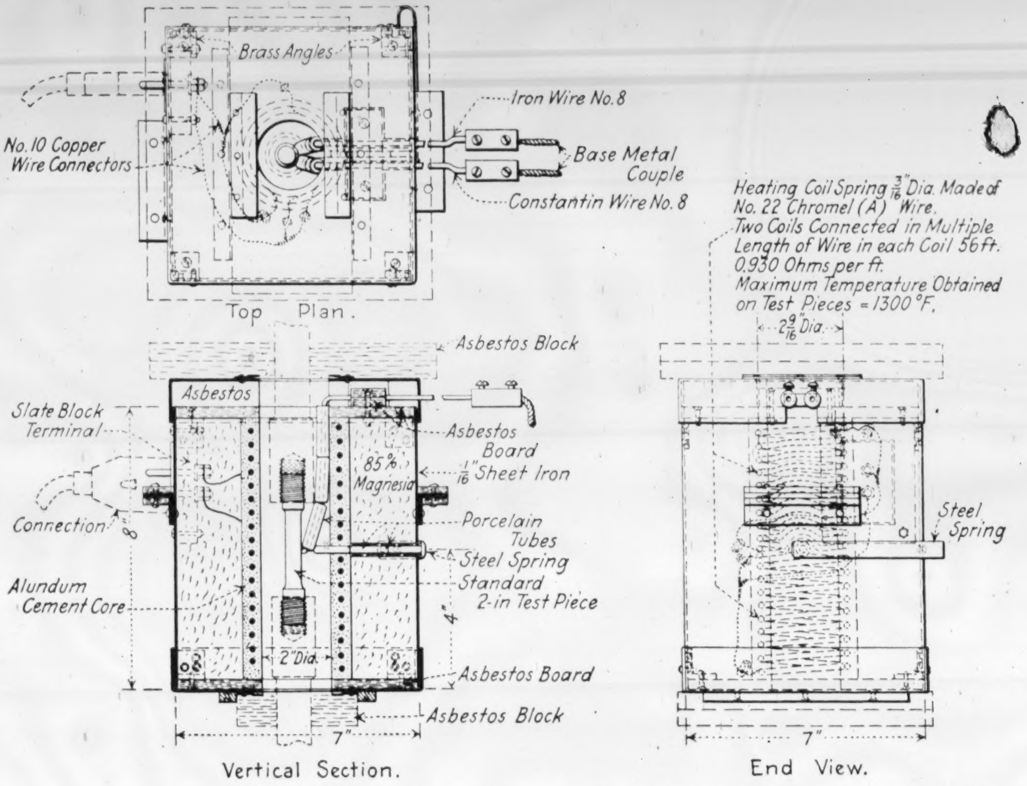

Brass Angles
No. 10 Copper Wire Connectors
Iron Wire No. 8
Base Metal Couple
Constantin Wire No. 8
Top Plan.
Heating Coil Spring $\frac{3}{16}$" Dia. Made of No. 22 Chromel (A) Wire.
Two Coils Connected in Multiple
Length of Wire in each Coil 56 ft.
0.930 Ohms per ft.
Maximum Temperature Obtained on Test Pieces = 1300 °F.
$2\frac{9}{16}$" Dia.
Asbestos Block
Asbestos
Slate Block Terminal
Connection
8"
Alundum Cement Core
Asbestos Board
85% Magnesia
$\frac{1}{16}$" Sheet Iron
Porcelain Tubes
Steel Spring
Standard 2-in Test Piece
4"
2" Dia.
Asbestos Board
Asbestos Block
7"
Vertical Section.
Steel Spring
7"
End View.

FIG. 12.—Diagram of Electric Heater Used by MacPherran, Showing Specimen in Position.

R. S. MACPHERRAN(158)

The furnace used is a heating box 7 in. square by 9 in. high. The hole in which the test specimen is inserted is 2 in. in diameter and is lined with a core of alundum cement wound with No. 22 chromel wire. This wire is wound in two coils, one over the top and one over the lower half of the alundum core. They are connected in multiple. The coils are first covered with alundum cement and then with magnesia. The thermocouple enters at the top of the box and runs down in such a position that the point is opposite the center of the test specimen. A spring on the outside of the box forces a porcelain rod through a hole against the base metal couple, holding the point against the test specimen. The temperature is measured with a Leeds and Northrup pyrometer using a base metal thermocouple. The apparatus is illustrated in Fig. 12.

The specimens used are the standard 0.505-in. test bars with threaded ends. All tests are held at constant temperature from 15 to 30 minutes before pulling. The proportional limit was not measured but the yield point was determined by the drop of the beam, and above 600° F. (315° C.) it was uncertain.

MacPherran states there are two ways to determine the temperature in testing metals at elevated temperatures: one with the thermocouple in contact with the outside of the specimen at the center of its gage length and the other by inserting it in the specimen outside the gage length. If the thermocouple is in contact with the surface of the specimen at the center, the test specimen cannot be hotter than the couple. If it is inserted in the specimen outside the gage length the couple cannot be hotter than the specimen. The possible error of the first method is to get temperature readings that are too high and of the second method to get readings that are too low. After carefully considering both methods the former was selected. It is possible that the higher temperatures found by several investigators are due to the placing of the thermocouple. It would seem, however, that there is more to be said in favor of the system adopted than for the one requiring the insertion of the thermocouple junction in the test specimen. It is very difficult to maintain a constant temperature for a considerable distance in the furnace tube, and it is believed by MacPherran that the temperature should be taken as near as possible to the point of rupture.

A series of tests were made with one thermocouple touching the outside of the center of the test specimen as in the regular tests, and another couple adjusted so that the point was in the exact center of a hole drilled through the specimen in the same horizontal plane as the point of the first couple. To protect the point of this second couple, the hole was then plugged with asbestos. The two couples therefore indicated the temperatures at the surface and center of the test specimen. To emphasize the difference between center and outside, a test specimen 0.75 in. in diameter was used in place of the regular 0.505-in. diameter bar. Three sets of readings were taken at temperatures in excess of 500° F. (260° C.) with the result that the center of test specimen was found to be 22 to 36° F. (12 to 20° C.) below the temperature of the outside of the bar. With the 0.505-in. bar this difference would

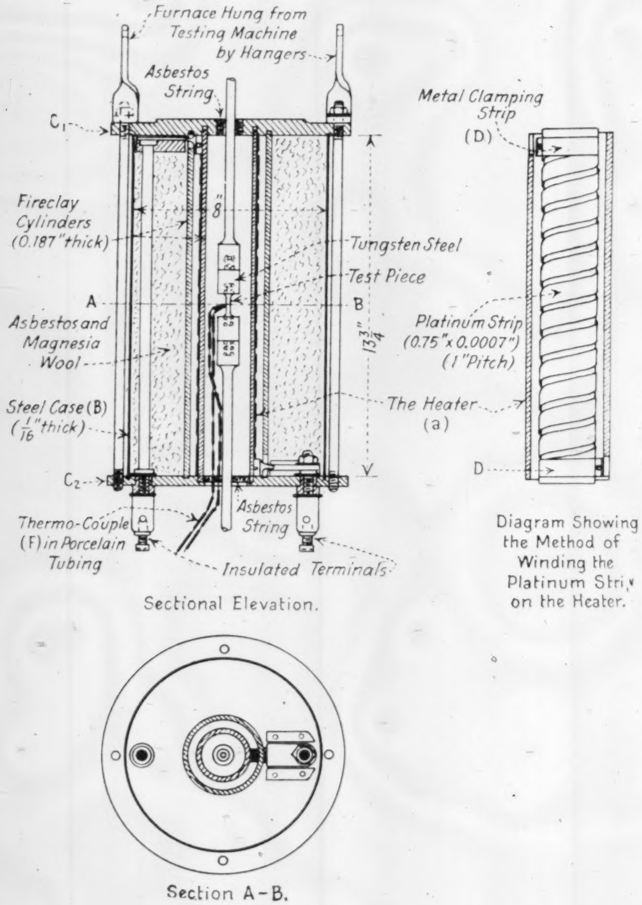
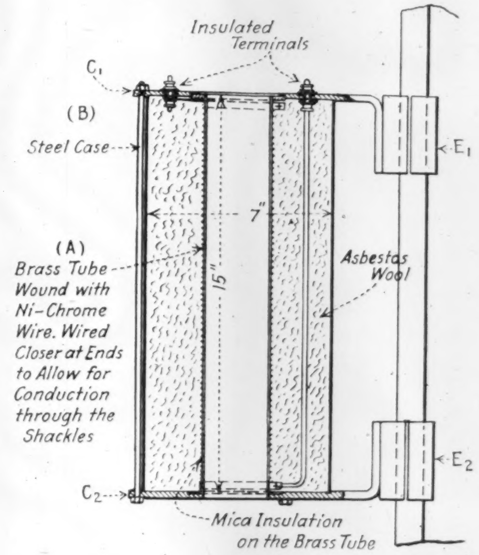
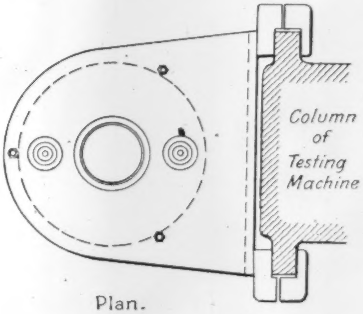

Furnace Hung from Testing Machine by Hangers
Asbestos String
C₁
Fireclay Cylinders (0.187" thick)
8"
Tungsten Steel
Test Piece
A
B
Asbestos and Magnesia Wool
13¾"
Steel Case (B) (1/16" thick)
The Heater (a)
C₂
Asbestos String
Thermo-Couple (F) in Porcelain Tubing
Insulated Terminals
Sectional Elevation.
Metal Clamping Strip (D)
Platinum Strip (0.75" x 0.0007") (1" Pitch)
D
Diagram Showing the Method of Winding the Platinum Strip on the Heater.
Section A-B.

FIG. 13.—Platinum High-Temperature Furnace of the National Physical Laboratory for Tension Tests.

of course be less. As the area represented by the outer layers is much greater than that represented by the center, MacPherran believes that the central outside thermocouple location as used in these tests gives a better indication of average temperature of the specimen under test.


Insulated Terminals
C_1
(B)
Steel Case
7"
(A) Brass Tube Wound with Ni-Chrome Wire. Wired Closer at Ends to Allow for Conduction through the Shackles
15"
Asbestos Wool
E_1
E_2
C_2
Mica Insulation on the Brass Tube

Sectional Elevation.


Column of Testing Machine

Plan.

FIG. 14.—National Physical Laboratory Furnace for Tension Tests up to 990° F. (600° C.).

NATIONAL PHYSICAL LABORATORY (169)

In the work of the National Physical Laboratory in England, two types of furnace were used in connection with a vertical testing machine.

A platinum furnace, Fig. 13, was used for temperatures up to 2200° F. (1200° C.), the heating element consisting of a platinum strip 0.75 in. by 0.0007 in. and wound on a fire-clay cylinder with an outside diameter of $\frac{2}{25}$ in., a thickness of 0.187 in. and a length $13\frac{7}{8}$ in. The ends of the strips are clamped in position on the cylinder by metal clips. A steel case surrounds the heater, and the space between the two is packed with asbestos and magnesia wool. The whole apparatus is clamped between two end plates on one of which two insulated terminals are fixed, these being connected to the two ends of the platinum heating coil. The furnace itself is suspended from the top shackle of the testing machine and uses a current of 15 amperes and 105 volts.

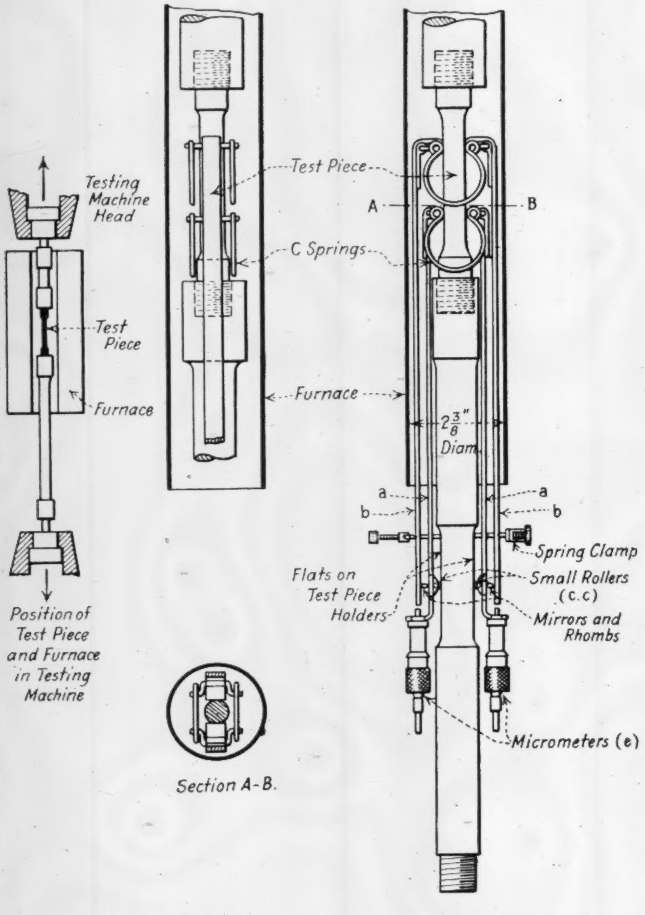

Testing Machine Head
Test Piece
Furnace
Position of Test Piece and Furnace in Testing Machine
Test Piece
C Springs
Furnace
A
B
$2\frac{3}{8}$" Diam.
a
b
a
b
Spring Clamp
Small Rollers (c.c)
Flats on Test Piece Holders
Mirrors and Rhombs
Micrometers (e)
Section A-B.

FIG. 15.—National Physical Laboratory High-Temperature Extensometer.

The second furnace used is for temperatures up to 1100° F. (600° C.) and is shown in Fig. 14. The heating element consists of nichrome wire wound on a brass tube. The tube is bound with mica, before winding the wire, in order to insulate it, and asbestos string is wrapped over the wire so as to keep the wire in position when it expands with the temperature. The heating chamber is surrounded by a steel shell 7 in. in diameter and the space between the shell and heating element is filled with asbestos wool. Two steel plates are bolted together clamping the heater and outer shell between them, and are arranged to connect the furnace to the frame of the testing machine. The ends of the heating coil are connected to two insulated terminals on the top plate. No. 18 nichrome wire is used for the heating element. The wire is coiled closer to the ends to allow for conduction of heat through the grips of the testing machine and to give a more uniform heating over the central three to five inches of the furnace. The temperature is measured with a thermocouple placed at the outside middle section of the gage length and protected by a porcelain tube.

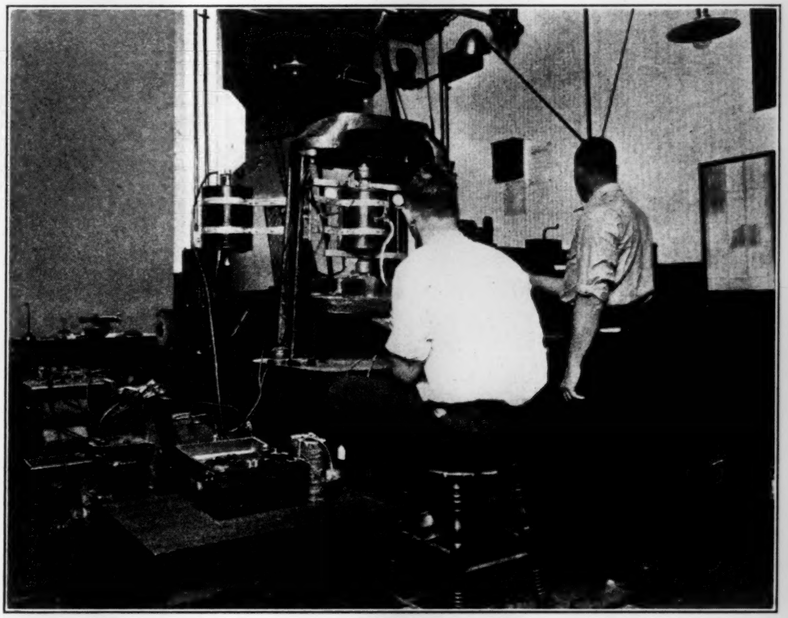


FIG. 16.—Apparatus Used by Malcolm in Tension Tests at High Temperatures, Showing Furnaces, Transformers, Potentiometer and Elastic Limit Apparatus.

The extensometer used is a combination of the best features of both Rudeloff's and Lea's extensometer and had two micrometers for measuring extension beyond the elastic limit. The clips are attached to the reduced part of the test piece by springs and protrude from the furnace. The inner clips are guided on flats on the test piece holders by small rollers. Mirrors and rhombs are placed between the clips and the whole is clamped together by a special spring attached to notches on the outer clip. The extension of test pieces causes relative movement of the clips and therefore rotation of the mirror rhombs which is measured in the usual way by a telescope and scale. The relative movement of the clips is also measured by two micrometers attached to the inner clips and working against the outer ones. Sketches of these extensometers are shown in Figs. 1 and 15.

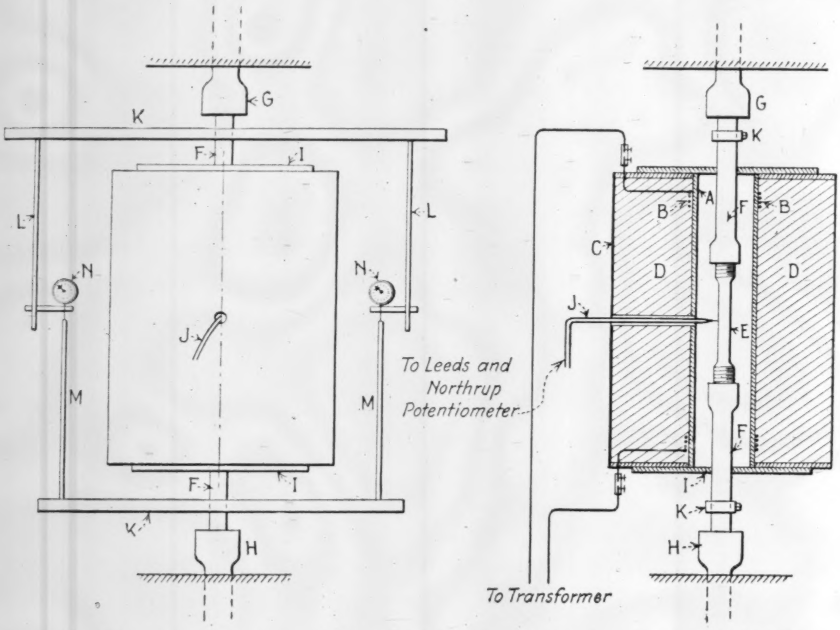


FIG. 17.—Diagram of Apparatus Used by Malcolm in Tension Tests at High Temperatures, Showing Specimen in Place and Location of Thermocouple.

V. T. MALCOLM (188, 189, 203, 212)

The tension tests of metals at elevated temperatures are made on a 100,000-lb. standard Olsen testing machine.

Pyrometers.—The pyrometer equipment consists of a portable Leeds and Northrup indicating potentiometer and thermocouples of 0.025-in. (No. 22) alumel and chromel wire.

Furnace.—The furnace equipment was made in duplicate in order to facilitate the heating and testing of specimens. The furnaces are attached to the outer leg of the testing machine by hinges so that they swing alternately into place between the heads for testing purposes. The general arrangement of apparatus is shown in Fig. 16, and Fig. 17 shows a section of the furnace with specimen in place and with extensometer gages attached and pyrometer inserted.

The test bars used are machined in the form of the standard 2-in. screw-end tension specimen 0.505 in. in diameter as shown in Fig. 18. In addition, special bars were used for calibration tests for each of the various metals tested, and were also used for certain temperature explorations and calibrations of the furnace. (See Fig. 19.)

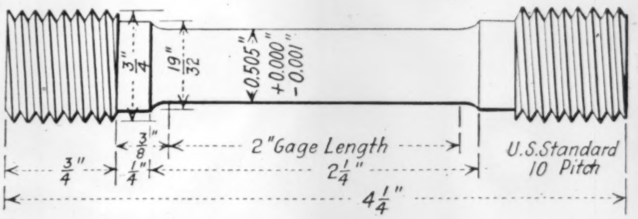


FIG. 18.—Test Specimen Used by Malcolm in High-Temperature Tests.

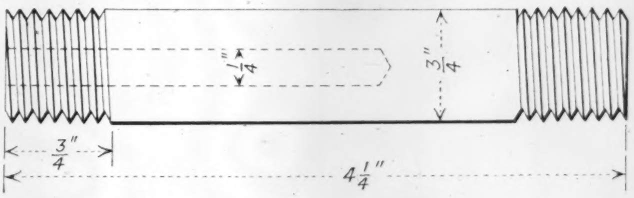


FIG. 19.—Calibration Bar Used by Malcolm in High-Temperature Tests.

In Fig. 17, *A* is an alundum tube upon which is wound the heating element *B*. This heating element is connected to the secondary of a transformer. The tube *A* is held in the container *C* and the space between *D* is filled with kieselguhr. The specimen under test, *E*, screws into the specimen holders *F*, which in turn screw into the testing machine adaptors *G* and *H*. *G* is the fixed member and *H* the moving member. When the specimen is in position, the doors *I* are closed and the thermocouple *J* placed against the test specimen at its mid-point. The doors *I* are made of asbestos board and fit snugly around the holders *F* so that no air currents can get into the heating chamber. As a further precaution against air currents, asbestos rope is wound around the holders *F* just inside the doors *I*. Arms *K* are rigidly fastened to specimen holders *F*. The rods *L* are fastened to the upper arm *K* and rods *M* to the lower arm *K*. Ames dial gages are connected to the fixed rods *L* and rest on the moving rods *M*.

Method of Test.—The test specimen is inserted in the heating unit and fixtures described. After the specimen has been at the desired temperature for at least one-half hour, an initial load of 100 lb. is applied in order to eliminate all lost motion. The Ames gages are then set at zero after which equal increments of load are applied and simultaneous readings of gages recorded. The size of the increment applied depends upon the kind of material under test and varies from 100 to 500 lb. Observations of elongation per increment of load are recorded until the yield point is passed. The Johnson elastic limit is then determined from a curve drawn through points obtained by plotting the elongation per increment of load.

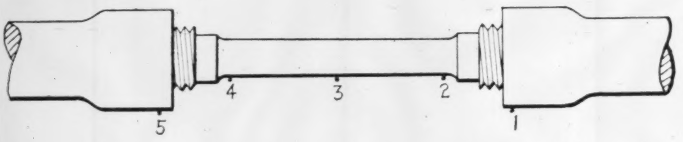


FIG. 20.—Sketch Showing Temperatures at Various Points of Test Specimen in Tests by Malcolm.

TEMPERATURES OF SPECIMENS AT POINTS INDICATED

Point No. 1		Point No. 2		Point No. 3		Point No. 4		Point No. 5	
deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.
295	146	330	166	365	185	308	153	273	134
508	264	547	286	600	315	521	272	477	247
677	358	738	392	791	422	717	381	636	336
877	469	938	503	991	532	921	494	832	444

DIFFERENCES IN TEMPERATURE AT POINTS INDICATED FROM THAT AT POINT 3

Point No. 1		Point No. 2		Point No. 3		Point No. 4		Point No. 5	
deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg Fahr.	deg. Cent.	deg. Fahr	deg. Cent.	deg. Fahr	deg. Cent
−70	−39	−35	−19	0	0	−57	−32	−92	−51
−92	−50	−53	−29	0	0	−79	−44	−123	−68
−114	−63	−53	−29	0	0	−74	−41	−155	−86
−114	−63	−53	−29	0	0	−70	−39	−159	−88

General Discussion of Accuracy of Test Results.—The accuracy of the results obtained in testing metals at elevated temperatures depends upon (1) the rate at which the load is applied, (2) the length of time the specimen is held under load at a given temperature, (3) the accuracy of the thermocouple and (4) the true temperature of the material under test. These points will be considered in order.

1. In general it may be said that the faster the rate of load application, the higher the tensile properties. In the author's tests a slow rate was used in order to observe the deformations which were plotted to determine the elastic limit. In this respect, the values reported are on the low side as compared with values at ordinary testing speeds.

2. The tensile properties decrease with the length of time the specimen is held under load at a given temperature. This may be dismissed from consideration inasmuch as all specimens were tested in approximately the same length of time—which was short.

3. In order to determine the accuracy of the thermocouples, the following procedure was adopted: One of the thermocouples used was checked against a standard and was found to be correct within experimental error. All other thermocouples used were then checked against this one and found to be within the limits of experimental error.

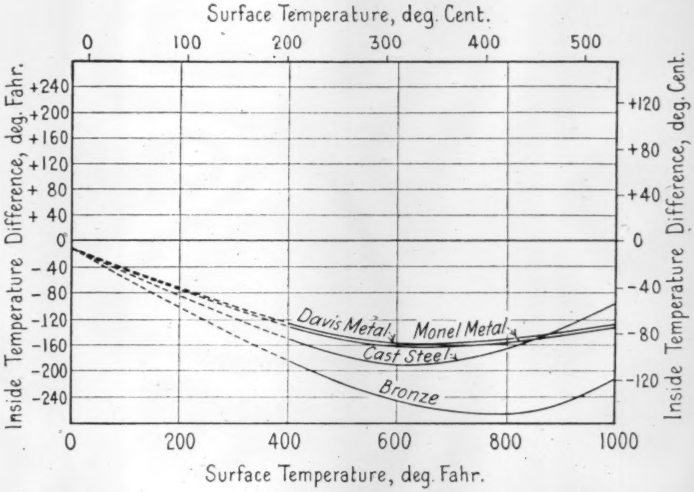


FIG. 21.—Malcolm's Temperature Calibration Chart.

4. The fourth point, regarding the true temperature of the bars, appears simple on its face, but after some of its phases are considered it is found to be very complex. The temperature of a specimen itself may vary in two ways: (*a*) From point to point along the surface and (*b*) from the surface to the center. The variation in temperature along the surface is easily determined by fastening the thermocouples to the points whose temperature is desired. The temperature of three points along the surface of the pull section of the specimen have been determined, namely, at the top fillet, at the mid-point, and at the bottom fillet. The results are shown in Fig. 20.

In order to determine the difference in temperature between surface and center of this specimen, a set of test bars known as calibration specimens were used. These bars were $\frac{3}{4}$ in. in outside diameter, with a $\frac{1}{4}$-in. hole bored from one end to $\frac{1}{2}$ in. beyond the center. This gave a wall thickness of $\frac{1}{4}$ in., equivalent to one-half the diameter of the standard $\frac{1}{2}$-in. bar. A thermocouple was placed against the outside, as was done in the regular tests, and another couple inserted in the longitudinal hole, both registering the temperature at the same section with $\frac{1}{4}$ in. of metal between. The whole apparatus was placed in the testing machine under the same conditions that obtained during the regular tests and comparative observations made from room temperature to 1000° F. (540° C.) The temperature difference observed on several materials tested were plotted as shown in Fig. 21.

One of the specimens was then suspended in the furnace by means of a wire, with grips removed, the thermocouples being in the same relative positions, and the temperature observations duplicated. The thermocouple readings with this set-up coincided within the limits of experimental error, which indicates that the difference in temperature between surface and center is due to loss of heat by conduction to adaptors, holders, extensometer arms, etc.

Although the apparent difference in temperature is indicated to be 146° F. (80° C.) as the maximum at 600° F. (315° C.) with the calibration bar used, this apparent difference exceeds appreciably the true difference existing between the surface and the center of the standard $\frac{1}{2}$-in. specimen. The reasons for this are as follows:

When these differences are considered in connection with the temperature differences noted along the surface, the existence of isothermals along the specimen must be assumed, which does not seem warranted.

The rate of heat transfer along a bar which is not at uniform temperature may be represented by the equation:

$$\frac{dH}{dt} = \pi r^2 K \frac{dT}{dl}$$

where $\frac{dH}{dt}$ = rate of heat flow,

πr^2 = area,

K = coefficient of conductivity, and

$\frac{dT}{dl}$ = rate of change of temperature with change in distance from the hotter portion.

From this equation it will be seen that the rate of flow of heat and therefore the temperature difference varies directly with the area.

Reference to the calibration bar will show that the area is twice the area of the standard specimen. Inasmuch as the area is the only varying quantity between the two equations for standard and calibration bars, it is apparent that from this correction alone the temperature difference between surface and center would be reduced very materially below the apparent differences shown. Assuming that there is a temperature gradient between points on the surface of the standard test bar and the center of the section through any of these points, the temperature measured at the surface would approximate more closely the mean effective temperature, which would lie at the point of mean effective area, namely, one-third the distance in from the surface of the bar. For this reason, the temperature as registered by a thermocouple placed against the mid-point of the specimen has been used by the author.

Referring particularly to variations in temperature along the length of the pull section of the standard test bar, observations of the manner in which the bars broke, under load, cast considerable doubt on the possibility of there being any appreciable difference in temperature along the bar.

Considering, therefore, all the experimental and theoretical observations made, we are of the opinion that the effective temperatures, whether they be in the center of the bar or at the ends, do not vary more than 40° F. (22° C.), and from the temperature indicated by the pyrometer, in some cases may be considerably less.

The work of Speller(215), Germer and Woods(209), d'Arcambal(148) and several other investigators, shows that the tendency of present investigation is to use the cylindrical electric furnace, with the thermocouple wire placed against the outside surface of the test specimen.

Before leaving the subject of tension tests of metals at elevated temperatures to discuss special tests of metals at various temperatures, tests of Jeffries and Sykes on wires at both low and high temperatures will be described.

ZAY JEFFRIES(127) AND W. P. SYKES(163)

The investigations of Jeffries and Sykes were mainly in connection with copper, tungsten, Armco iron, nickel and molybdenum wires and the methods of test will be described in detail. In these tests wires were subjected to tension at temperatures from −310° F. (−190° C.) to maximum of 1650 to 1830° F. (900 to 1000° C.). No attempt was made to determine the elastic limit but the other tensile properties, namely, tensile strength, elongation, and reduction of area, were determined at all temperatures.

The apparatus used for these tests is composed of two main parts, the base and the loading mechanism. The base consists of two cast-iron disks, a bottom and a top, that are fastened together by three pieces of steel pipe. The base weighs a little over 100 lb. and is placed on a platform scale. The top of the base portion is provided with a steel tube 0.875 in. in outside and 0.5 in. in inside diameter to which the test pieces are clamped by special clamps. The upper clamp is connected with the loading mechanism. When the load is applied by the handwheel, the test wire pulls on the base and the amount of its pull is measured on the weighing mechanism of the scale. The zero point on the scale is equal to the weight of the base; the scale is kept balanced continually during the test until the wire breaks. The scale reading at the breaking load of the test specimen is then subtracted from the zero reading and the difference gives the breaking load of the specimen.

Liquid Air Tests.—Punch marks 2 in. apart were made on all wires and the clamps were set about 2.5 in. apart, leaving about 0.25 in. between each clamp and the closest punch mark. The test wires were locked in clamps and inserted in the machine and a 1-qt., wide-mouth thermos bottle of the food-jar type, more than three-quarters filled with liquid air, was raised in such a manner that the steel tube containing the test wire was immersed in liquid air. The test wire was completely immersed and hence its temperature was that of boiling liquid air. As soon as violent boiling ceased, the load was applied until the wire broke. The vacuum jar containing the liquid air was then lowered from the steel tube and another vessel containing warm water was substituted for it. When the temperature had been raised by water the clamps were removed.

Tests at 212° F. (100° C.).—These tests were made in boiling water. An electric percolator heater was placed on the platform instead of the vacuum jar and a coffee pot was used for holding the water. The water was kept boiling vigorously till the end of the test.

Tests at 400° F. (200° C.).—These tests were made in hot crisco. Crisco was used because it could be heated to 480° F. (250° C.) with very little volatilization; one of the chief advantages of crisco is that it is very fluid at higher temperatures. The crisco was heated in the same electric heater that was used in the 100° C. tests. The temperature during the test may have varied 3 or 4° C. Several pounds of crisco, however, were used so that the temperature changes were slow. Immediately after each test piece broke, the temperature of the crisco was measured with a mercury thermometer.

Tests above 400° F. (200° C.).—A different scale and different loading mechanism were used and the base of the apparatus modified so that an electric furnace could be used to obtain the proper temperature. A Kron scale with a 30-in. dial graduated in quarter pounds but sensitive to less was used. The electric furnace consisted of an alundum tube 1 in. in inside diameter, and 12 in. long, wound with nichrome ribbon enclosed in a gas-tight steel cylinder. Powdered silica was used as a heat insulating medium between the alundum tube and the cylinder. The cylinder was provided with a connection to a tank of compressed argon, so that a neutral atmosphere could be maintained in the furnace at higher temperatures. The electric furnace was so fastened that the load on the wires was transmitted to the base portion by the lower end of the furnace. The bottom clamp was flanged to fit a seat at the bottom of the furnace housing; the flange was so large that it could not be drawn through the furnace tube. This clamp was fastened to the loading mechanism by means of a clevice.

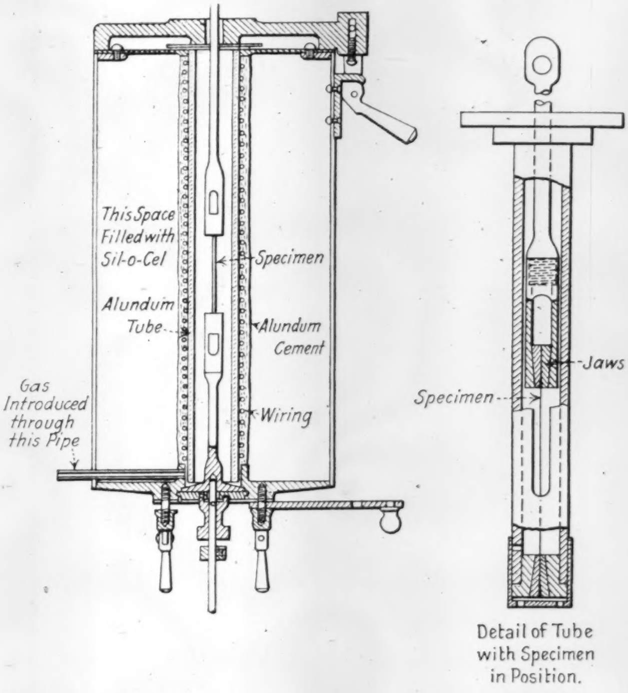

This Space Filled with Sil-o-Cel
Specimen
Alundum Tube
Alundum Cement
Gas Introduced through this Pipe
Wiring
Jaws
Specimen
Detail of Tube with Specimen in Position.

FIG. 22.—Diagram of Furnace Used by Jeffries and Sykes for the Testing of Metals at High Temperatures.

A platinum-platinum rhodium thermocouple was used to measure the temperature. The hot junction was placed in the furnace tube about half way between the two clamps, that is, at about the central point of the test wire. The thermocouple was connected with a Wilson-Maeulen galvanometer with both millivolt and temperature scales. The temperature of the electric furnace could be maintained constant with a wire-wound rheostat.

Details of the furnace and tube with the specimen in position are shown in Fig. 22.

IMPACT TESTS

Guillet and Revillon(**60**) carried out tests on a Guillery 60-kgm. impact machine. The test pieces were heated in an electric furnace to slightly above the temperature required for the tests, they were then placed on the anvil and temperature noted at time of fracture. The temperature was determined by the use of a thermocouple inserted in a small hole drilled in the specimen and penetrating up to about 3 mm. from the cross-section to be fractured. The ends of the test pieces were covered with asbestos to prevent cooling of the extremities when in contact with the anvil. Tests at as near 212° F. (100° C.) as possible were obtained by using boiling water.

A. C. Langenberg(**200, 201**) has made impact tests at Watertown Arsenal at the following temperatures: −80, −40, −20, 0, 15, 32, 50, 70, 90, 110, 130, 150, 175, 200, 225, 250, 350, 500, 750 and 1000° F. (−60 to 540° C.), two test specimens being tested at each temperature. Temperatures below the atmospheric were obtained by immersing the test bars in a bath of acetone. The acetone bath was cooled to the desired temperatures down to 0° F. (−18° C.) by means of a calcium-chloride solution cooled by an ordinary ammonia refrigerating apparatus. The lower temperatures were obtained by direct addition to the acetone of carbon dioxide snow. Temperatures from 90 to 350° F. (32 to 175° C.) were obtained by heating the test bars in a Freas constant temperature oven, and from 500 to 1000° F. (260 to 540° C.) the test bars were heated in a Hoskins electric muffle furnace.

The lower temperatures were ascertained by alcohol thermometers, the medium by mercury thermometers, and the higher temperatures by means of platinum-platinum rhodium thermocouples. In tests from −80 to 350° F. (−60 to 175° C.) a thermometer was inserted in a hole drilled in a dummy test specimen and packed with magnesium powder, the dummy and thermometer were placed in the cooling bath or heating furnace in the center of the group of test bars. An additional thermometer indicated the temperature of the heating or cooling medium. When two thermometers gave readings as near alike as it was found possible to obtain, the temperature of each test bar was considered to be very close to the temperature of the dummy test bar as shown by the inserted thermometer. At temperatures from 500 to 1000° F.

(260 to 540° C.) a thermocouple was inserted in the center of the notch of each test bar and the bar was tested when the thermocouple showed that the desired temperature was reached.

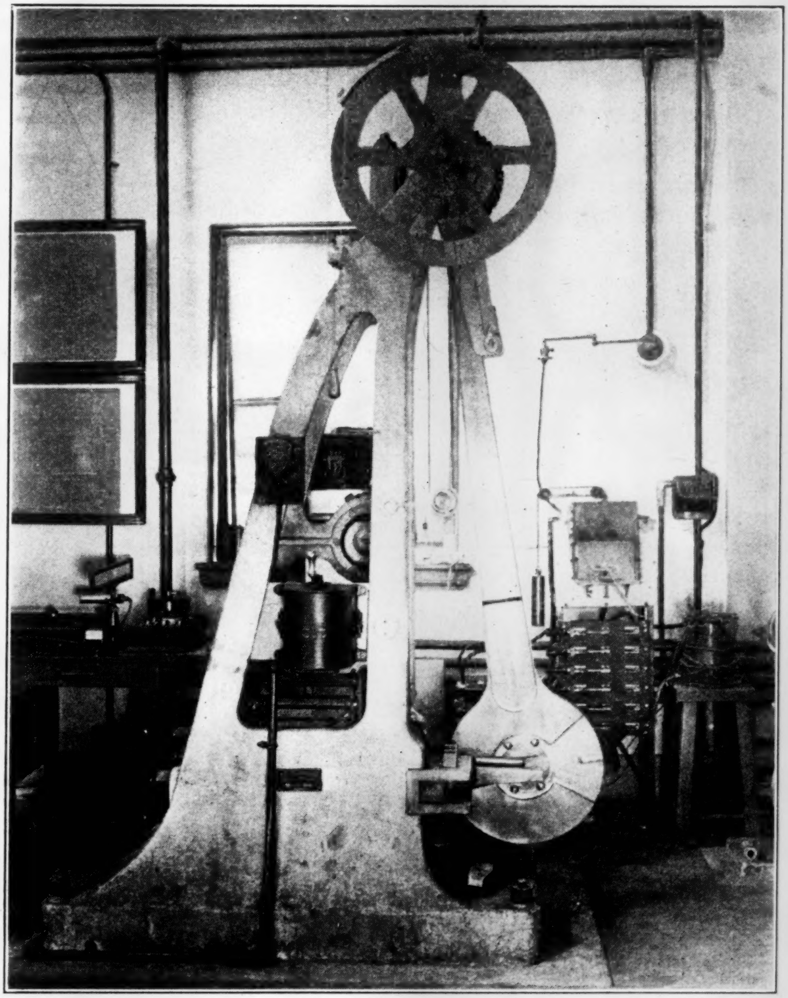


FIG. 23.—Charpy Impact Testing Machine Used by Langenberg.

In testing, the heating or cooling apparatus was placed as conveniently near the impact testing machine as possible, and each specimen transferred quickly to the machine, the time in transferring being observed by means of a stop watch. It was found that the temperature of the test bars at the moment of impact closely approximated the desired temperature and it is believed that each specimen was tested at a temperature within 2° F. above or below the temperature recorded.

The large Charpy impact machine used in the tests (Fig. 23) has the following constants:

Weight of pendulum	212.3 lb.
Velocity of impact	25.7 ft. per second
Capacity	2199.5 ft-lb.

The specimen used in these tests was the large notched Charpy impact specimen, 6.102 in. long and 1.181 in. square in cross-section, with the notch 0.591 in. deep by 0.158 in. wide.

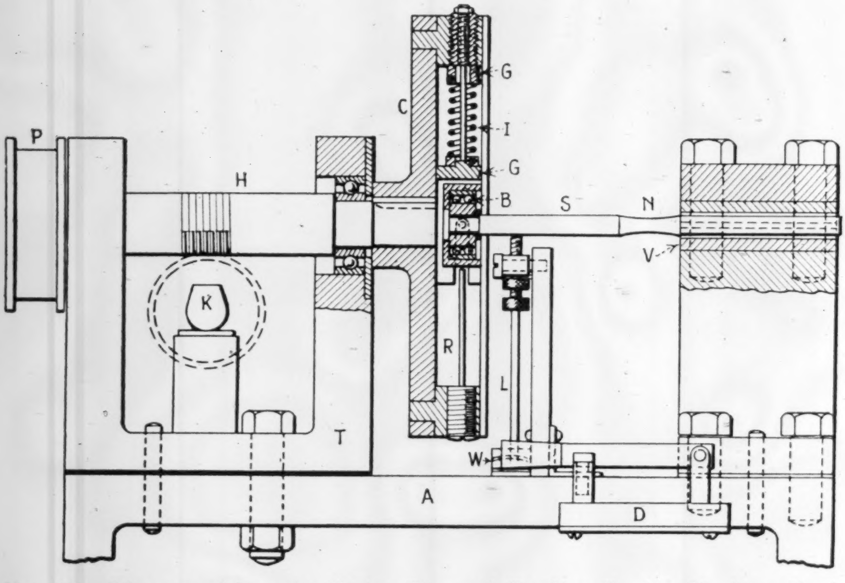


FIG. 24.—Diagram of Rotating-Spring Reversed Bending Testing Machine Used by Moore.

ALTERNATING STRESS TESTS

Not a great amount of research work has been carried out on the effect of various temperatures on the strength of materials under alternating stress. Tests were made by Batson and Hyde(89) at the National Physical Laboratory in England in a machine of the Wohler type, the test piece running at a speed of 2000 alternations per minute in an oil bath heated electrically.

During the past year a considerable number of repeated stress tests of steel at temperatures up to 875° F. (465° C.) have been made in the laboratory of the Investigation of the Fatigue of Metals at the University of Illinois(213) under the direction of Prof. H. F. Moore with the cooperation of the National Research Council, General Electric Co., Illinois Engineering Experiment Station, Engineering Foundation, Western Electric Co., Allis-Chalmers Manufacturing Co., and the Copper and Brass Research Association. The testing machine used in these experiments is shown in Fig. 24 and is a reversed-bending testing machine. In this machine one end of the specimen *S* is held rigid in the vise of *V* and the other end which runs in the bearing *B*, is rotated in a small circle. Sidewise pressure, which can be adjusted by means of a screw, is brought on the bearing *B* by a calibrated indicator spring *I*. The compression of the spring, and hence the load on the specimen, is measured by means of a strain-gage spanning the gage holes *GG* shown near the ends of the spring. The rotating spring is carried in the cross-head *C*. Sidewise motion of the bearing *B* is prevented by placing the bearing in a slot, and excessive displacement of the bearing, when the specimen breaks, is prevented by the rod *R*. The cross-head is driven by a shaft *H*, a pulley *P*, and a motor not shown in the figure. The number of revolutions of the cross-head is measured by the revolution counter *K* which is driven by a worm on the drive-shaft *H*. When a test to destruction is carried out, the fracture of the specimen occurs at the necked-down part *N*, and the broken end of the specimen hits a screw and kicks out a lever *L*. This releases the spring *W*, which then opens the motor switch *D*, thus stopping the motor.

In the elevated temperature investigation a small electric furnace not shown in the figure was added in order to heat the specimen to the required temperature for test. Temperatures were measured by means of a thermocouple in contact with the specimen at its region of maximum stress and temperature was recorded and controlled by a Leeds and Northrup temperature recorder and automatic controller.

Endurance limits (fatigue limits) for completely reversed stress were determined from *S-N* diagrams described in *Bulletins Nos. 124* and *136* of the University of Illinois.

The results obtained by Moore are regarded for the present merely as preliminary. They do, however, give certain interesting indications, and we may expect to find some startling results in tests of this nature as the work progresses.

TORSION TESTS

Bregowsky and Spring made a number of torsional tests on rolled rods at elevated temperatures. In order to insure as nearly comparable results as possible, rods of the same size ($1\frac{1}{8}$ in. in diameter) were purchased in the market and test bars cut off and turned down to uniform diameter of 0.855 in. The length of the turned-down section was 8 in. in nearly all cases.

The same sort of heating apparatus was used as noted under tension tests by Bregowsky and Spring(83). The coil was 12 in. long. Fig. 25 shows the bar and appratus in position. For high temperature, mica plates and asbestos sheets were inserted between the jaws and head of the testing machine to retard the loss of heat.

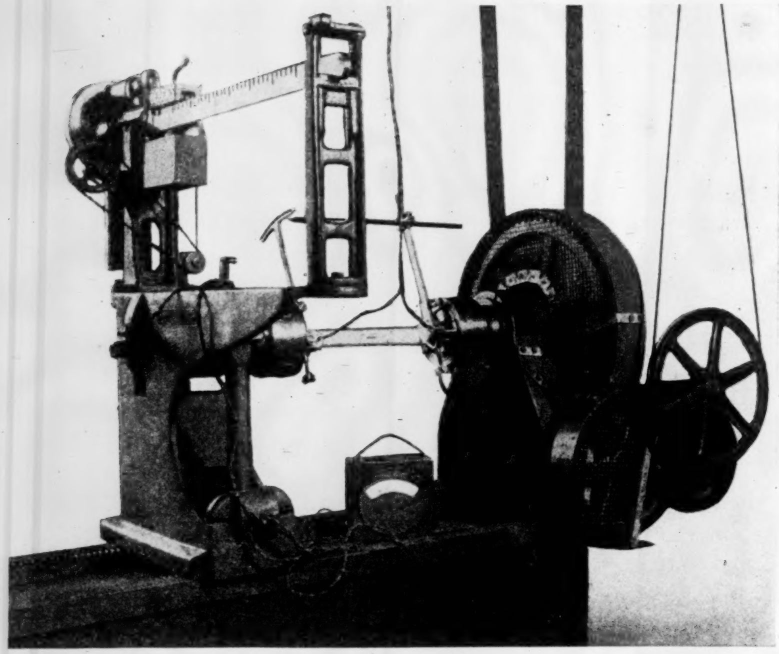


FIG. 25.—Torsional Machine Used by **Bregowsky and** Spring with Test Specimen and Apparatus in Place.

Elastic limits were determined by plotting readings taken by means of the troptometer, with increments of load, applied very slowly and the corresponding distortion read off the scale. Ultimate strength and elastic limit were given in pounds per square inch and total twist in turns (revolutions of 360 deg. each) with number of degrees in excess.

HARDNESS TESTS

Aitchison(123) gives some results of hardness tests at elevated temperatures on high-speed steels of various compositions. Prof.

C. A. Edwards(120) recently carried out a series of investigations into the hardness of steels at elevated temperatures and in order to readily compare his work with the standard Brinell machine he had to develop an entirely new apparatus.

This hardness testing at elevated temperatures is of great advantage in order to determine the cutting efficiency of tools at various temperatures, and a simple accurate hardness test at elevated temperatures is certainly needed to-day. As this method of test is really in process of development, little can be stated at this time regarding the testing or apparatus.

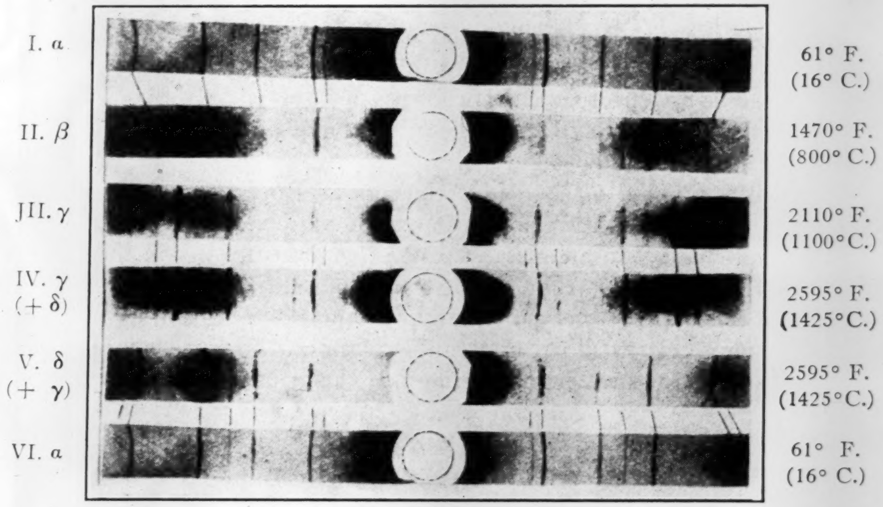


FIG. 26.—Photograms of Pure Iron at Different Temperatures.

X-RAY SPECTROGRAPH

Arne Westgren(165) of Gothenburg has carried out in the Physical Institute of the University of Lund, Sweden, quite an amount of interesting and instructive work with the X-ray spectrograph on iron and steel at elevated temperatures. Lately the X-ray has been used to study the defects in iron and steel castings and it has opened up a field that is both instructive and fascinating. While the X-ray analysis is in its infancy, the writer believes that it will be one of the future methods of testing metals and alloys at various temperatures.

Westgren has shown the importance of the X-ray method of investigation in metallographic research of iron and steel, both at ordinary and elevated temperatures. According to the spectrograms obtained at elevated temperatures it has been shown that a fundamental difference exists between the apparent transformation point A_2 and the critical point A_3. Westgren reported he was unable to find any structural change of iron either above or below the A_2 point. At A_3, however, he finds the atoms of iron are completely rearranged and the iron passes from one crystal class into another. Consequently, the difference between iron of the alpha and beta states is not of the same kind as between the alpha and gamma states. Fig. 26 is a photogram of pure iron at different temperatures.

This investigation has shown that the iron atoms of martensite are oriented in exactly the same way as ferrite, and the difference in hardness between these two structural constituents is not due to the iron but to the carbon present in the martensite. This has an important bearing on the testing of metals at elevated temperatures, for by the use of the X-ray spectrograph, problems now solved only by empirical methods may be open to theoretical treatment and become based on rational scientific knowledge.

It is the belief of such investigators as Rosenhain, Jeffries and Lester that the real future advancement of a knowledge of the internal structural changes in metals at various temperatures lies in the direction of the X-ray spectrum. It is to be hoped that investigators will actively take up this very interesting method of research, as it gives great promise of revealing, in a simple manner, the more complicated problems of structural changes in metals at various temperatures.

LONG-TIME TESTS

In the foregoing series of tests the time consumed in most cases has been so short as to give little idea as to the probable behavior of the metals or alloys when maintained for considerable periods under the applied conditions of stress and temperature. Recent experimental work by J. H. S. Dickenson(173), calls attention to the influence of the time factor in determining the temperature up to which certain steels can support a given load and, by inference, the load which can be borne at any given temperature.

Two series of tests were run by Dickenson, one to determine duration at constant load and constant temperature, and the other at constant load and uniform rate of temperature increase. In both series of tests a load of 19,000 lb. per sq. in. on the specimen was used and the temperature varied from 932 to 1769° F. (500 to 965° C.). The tests were carried out on six samples of steel made into bars of 8-in. gage length and 0.40 in. in diameter.

The tests were carried out with one exception on heat-treated steel, the exception being a cast chrome-nickel steel. The apparatus used was arranged for six tension tests simultaneously, with electric furnaces wired in parallel, the temperature being recorded by a Cambridge thread recorder, the couples being checked before and after use. The testing machines were of special construction and designed for this investigation.

Duration Tests at Constant Load and Constant Temperature.—In conducting these tests, care was taken in applying the load so that no live load was momentarily produced and the temperature was steadily increased to the desired point where it was maintained day and night until fracture occurred or until it was deemed unnecessary to continue. A daily measurement was made of the change in distance between the gage points on the specimen, this measurement being readily obtained because the gage marks were outside the furnace. More frequent observations were made when rapid extension of the specimen required it or when rupture became imminent at the end of long runs.

A series of test pieces for each class of steel was run at 90° F. (50° C.) ranges, such as 1022 to 1112° F. (550 to 600° C.), 1112 to 1202° F. (600 to 650° C.), and so on.

Tests at Constant Load and Uniform Rate of Temperature Change.—In these tests, after the test piece had been placed in position in the furnace and the load applied, the gage length was measured. The temperature was slowly raised by means of a specially constructed rheostat at the uniform rate of 180° F. (100° C.) per hour, an over-all measurement being made at 212° F. (100° C.) and thereafter on reaching each additional 90° F. (50° C.), care being taken to make this coincide with half-hourly periods. Later as the rate of extension increased, more frequent measurements were made, usually in six-minute periods and finally the temperature at which the test specimen fractured was carefully noted.

Tables were worked out and graphs made, showing estimates of the probable lives of test specimens subjected to constant load and temperature for long periods, and eventually withdrawn but not broken. An estimate of the probable time before rupture would have occurred, had the test proceeded, was obtained in each case by comparing the time required to produce the same extension in unbroken and broken specimens of the same steel. The estimates given, however, are only of general interest.

In 1922 the author(188, 189) carried out a series of tests for 400 hours on cast steel at constant load and constant temperature. The standard A.S.T.M. test bars were used, of 2-in. gage length, 0.505 in. in diameter and the apparatus used was the same as described in the tension tests. The temperature of the specimen was raised at a uniform rate until a maximum of 1100° F. (600° C.) was reached, and a load of 21,000 lb. per sq. in. placed on the specimen. This temperature and load were maintained night and day for 400 hours, after which the load was removed and the temperature allowed to drop to normal. The original gage length was remeasured for any permanent extension or deformation.

The U. S. Bureau of Standards is now working on apparatus for testing metals at constant temperature over long-time periods, but as yet little work has been accomplished.

A knowledge of the behavior of metals at elevated temperature over long periods would undoubtedly be of great technical importance for the reason that these tests tend to cast grave doubts on our ideas as to the yield point or elastic limit of certain metals in common use and it would appear that we may be compelled to revise our ideas along these lines. Since it is now generally agreed that design should be based on the yield point or elastic limit, the matter becomes important.

METALLIC OXIDATION AT ELEVATED TEMPERATURES

One neglected type of study in the testing of metals at elevated temperatures is the metallic oxidation of the metals or alloys when exposed to temperatures considerably higher than the atmospheric range, and more especially the attack of atmospheric oxygen upon the exposed metallic surfaces. That the problem is a difficult one to contend with is connoted by the practical dominance of a certain alloy in electric heating. Proprietary interest may account in part for the paucity of information available in technical literature upon even the most general facts on the behavior of metals and alloys when exposed to elevated temperatures. A very interesting and instructive paper on this subject was published by Pilling and Bedworth(191) in March, 1922.

Dickenson(173) published results of scaling tests on metals at elevated temperatures. In his experimental work eight typical steels were selected for examination. From each sample nine cylinders each 0.50 in. in diameter by 2 in. in length were machined, polished with emery and weighed. Each of these cylinders was heated for a total time of 100 hours. In order to maintain throughout the 100 hours a practically uniform rate of oxidation, which slows down as the adhering scale increases in thickness, the heating was carried out in 18 periods of approximately 5½ hours each, the specimens being scraped free from scale and weighed after each cooling. Two types of furnace were used for heating the specimens. An electric furnace surrounded by air was used for the lower temperatures, while for the higher ranges the less pure atmosphere of a gas furnace was employed.

In a table by Dickenson the scaling rate in ounces per square inch per hour at mean temperatures indicated is given, including the results from both electric and gas furnaces. It appears that the rate of scaling at 1600° F. (870° C.) is much the same in the two types of furnace, at any rate, when the gas muffle front is slightly open and burners are receiving full air as in the present case so that the lower series and the upper series may be considered satisfactorily linked.

A series of tests was carried out by the writer(**188, 189**) in 1922 on the rate of scaling of cast steel. In the experimental work 1-in. cubes were used, each cube being carefully ground on an emery wheel to remove any foreign substance adhering to it, after which they were carefully calipered and weighed. They were then subjected to 100 hours treatment in an electric furnace in which was maintained ordinary atmospheric conditions. In order to maintain a uniform rate of oxidation, the specimens were removed approximately every six hours and scraped free of adhering scale and weighed. A graphical chart was plotted showing the amount of scale in ounces at the temperatures noted. It was found from these tests that little or no scaling existed when steel was exposed to temperatures below 1100° F. (600° C.) and that the formation of scale started at about that temperature and increased rapidly, while at 1700° F. (925° C.) the amount of scaling may be considered excessive.

CONCLUSION

The writer has endeavored to describe in outline the latest methods of testing metals at various temperatures. It will be noted that the furnaces and other apparatus, procedure, etc., used by the various investigators differ to some extent and are by no means standardized, each investigator believing his method to be the correct one. Very little definite information on the rational mechanical testing of metals at elevated temperatures has been obtained.

The effect upon the physical properties of metals of raising the temperature cannot as yet be stated in terms of a definite law. It may be generally stated that the tensile strength and elastic limit of steel decrease and the elongation and reduction of area increase as the temperature is raised. Of course there are exceptions to this rule. It has been noted in nearly all the investigations that at certain temperatures between 500 and 800° F. (260 and 425° C.) the tensile strength rises and the elongation and reduction of area decrease, but the elastic limit continues to decline steadily. Therefore, to use the tensile strength as a basis of design would be far from correct. This condition of marked rise in the tensile strength and fall in the elongation and reduction of area is known as "blue brittleness" from the original German term "Krupp-Krankheit" and is to some extent the limit of our general knowledge. Rosenhain and Archbutt(130) found a formation of intercrystallin cracks, which eventually produced failure in boiler plate. These plates were used at elevated temperatures and it is thought that the long sustained load at these temperatures caused the amorphous cement at the grain boundaries to flow and eventually break without deformation of the grains. Jeffries(184) has made quite a study of the physical changes in iron and steel at various temperatures and the conclusions reached are both interesting and instructive. Langenberg(186) believes that "blue brittleness" is a distinctive property of free ferrite, and furthermore that "blue brittleness" is not the property of free ferrite at blue heat, but rather is a property resulting from a mechanical deformation of free ferrite at blue heat or lower temperatures. We believe that this is a subject that should be given careful consideration in the testing of metals at elevated temperatures.

Again, we find that results obtained in actual practice have not always been in accordance with those obtained experimentally. One instance with which the writer is acquainted is a set of valves operating at 950° F. (510° C.) for several years which are still giving excellent service, yet most of our experimental work in testing metals at elevated temperature shows that steel is very weak at this temperature.

The explanation of such inconsistencies is probably to be found in the fact that the alterations in the physical properties of metals and alloys due to variations of temperature are not always of the same nature. With any increase in temperature and consequent molecular activity we may expect a gradual falling off in tensile strength until at the melting point of the metal the tenacity becomes nothing. Allotropic changes in metals are accompanied by changes in physical properties. For instance, iron undergoes certain changes at certain temperatures. Zinc is brittle at ordinary temperatures but when heated to certain temperatures it becomes malleable and again loses this property at higher temperatures. Tin at low temperature undergoes a molecular change and falls to powder. Such changes are abnormal, and, except in the case of iron, very little is known as to what takes place when metals are alloyed and subjected to various temperatures.

Some metals and alloys undergo a gradual change in their crystallin character, which is greater at elevated or low temperatures. This change may be simply an increase in size of crystals or may be a change in crystallin structure. For instance, tests show that brass or bronze when heated to temperatures beyond 400° F. (205° C.) becomes very treacherous, the tensile strength and elongation both decreasing as the temperature is raised, and the crystal size becoming very coarse. Alloys containing two or more constituents are more likely to suffer failure at elevated temperatures than those containing only one constituent, especially if one of the constituents is a eutectic. The eutectic often has a melting point lower than the constituent metals and therefore its strength is affected at a lower temperature; and if the eutectic forms a network or cement around the grains or crystals, its strength represents the strength of the alloy.

In these several causes of failure, the gradual change of structure occurs only after a lapse of time, and this is one reason for failure of metals or alloys that have shown good results when tested in a short time at elevated temperatures. Tests carried out on an alloy at short duration are not always sufficient to indicate the behavior of a metal in service.

Another example which may be cited is the large columnar structure often found at certain temperatures in nickel-copper alloys.

Very little appears to be known about the changes that take place in metals or alloys when subjected to high-temperature service, and it seems advisable that a complete structural study with the aid of a microscope should be made of metals when tested at various temperatures. The microscope together with the X-ray will, we believe, be found valuable in future tests.

In summing up, we would say that in carrying out research into methods of testing metals at various temperatures, it should be our aim to carry out such tests as will approximate the trying conditions of service. This fact is often lost sight of in making an investigation. To be of any value the investigation should have a definite aim and be carefully planned. A general survey of the entire field should be made, as one method of test may be of value to a single consumer or producer, but of little or no value to others.

The author hopes that we will soon be able to standardize our methods of test in this field of great importance, in which, it may not be amiss to mention, continental Europe has made rapid progress.

AVAILABLE DATA ON THE PROPERTIES OF IRONS AND STEELS AT VARIOUS TEMPERATURES[1]

BY H. J. FRENCH[2] AND W. A. TUCKER[3]

INTRODUCTION

Despite the fact that attention has been called repeatedly during the past few years to the incomplete and unsatisfactory nature of available information on the properties of ferrous metals at high and low temperatures, a vast amount of test work has been carried out by many investigators. Not all of the results have been published but much of the information is now in print and there can be developed many interesting and important comparisons in addition to the special features emphasized in each report. However, it is not intended to present a complete résumé of all this material but rather to give a brief sketch of the character of published information. Detailed study of any of the phases covered in the literature may be made by consulting the references in the Bibliography which will be found appended to this paper.

No attempt will be made to reproduce or discuss results for all the ferrous alloys which have been tested nor can the tests made by all investigators of a given alloy be mentioned. However, there will be given representative graphs or other forms of data to show the general effects of temperature variations upon the properties of irons and steels, particularly with respect to those features of interest to engineers. Reference will also be made to some of the "heat-resisting" alloys now in use or proposed for high-temperature service.

MECHANICAL TESTS AT VARIOUS TEMPERATURES

IMPORTANCE OF THE TIME FACTOR AT HIGH TEMPERATURES

Before summarizing some of the principal features shown by the available data, attention should be called to the importance of the time factor in mechanical tests of metals at high temperatures. Howard(**17**)[4] reported that the "rate of speed of testing which might modify the results somewhat with ductile material at atmospheric temperature had a very decided influence upon the apparent tenacity at high temperature." Steel containing 0.81 per cent of carbon was tested at a slow speed which produced rupture in from 5 to 10 minutes and also under rapidly applied stresses (in which case the time was from 2 to 8 seconds). Nearly the same strength was displayed whether slowly or rapidly fractured at temperatures below about 600° F. (315° C.), this being a comparatively brittle metal at moderate temperatures. Above this temperature the apparent strength of the rapidly fractured specimens largely exceeded the strength of the others. The higher the temperature the wider apart were the results. An extreme illustration of this kind was furnished by a specimen tested at 1410° F. (765° C.) which when ruptured in 2 seconds showed a tensile strength of about 62,000 lb. per sq. in., whereas at ordinary speed of testing a corresponding bar fractured at 33,240 lb. per sq. in.

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[1] Published by permission of the Director of the U. S. Bureau of Standards.

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[4] The boldface numbers in parentheses refer to the papers of the Bibliography appended hereto, page 128.

TABLE I.—EFFECT OF SLOW LOADING ON THE TENSILE PROPERTIES OF FIREBOX BOILER PLATE AT DIFFERENT TEMPERATURES [FRENCH **(179)**].[1]

C, 0.19; Mn, 0.43; P, 0.020; S, 0.031

Temperature of Test		Rate of Loading	Proportional Limit, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Remarks
deg. Fahr.	deg. Cent.						
315	155	Adopted standard[2]	26,600	58,100	24.9	49.3	Average of 3 tests.
315	155	$6\frac{2}{3}$ hours from 22,000 to 47,000 lb. per sq. in.[1]	......	64,300	22.8	45.9	Average of 2 tests.
565	295	Adopted standard[2]	14,300	66,400	25.9	53.1	Average of 3 tests.
565	295	$3\frac{1}{2}$ hours from 9,000 to 20,000 lb. per sq. in.	......	60,000	36.0	59.2	
865	465	Adopted standard[2]	13,200	47,500	33.6	68.5	Average of 3 tests.
865	465	6 hours from 9,000 to 30,000 lb. per sq. in.	......	33,600	42.0	78.4	

[1] Note the apparently anomalous behavior with respect to rate of stress application at 315° F. (155°C.) as compared with higher temperatures.

[2] Adopted standard averages about 0.05 in. per minute extension.

Similar effects are observed in comparison of extremely slow and ordinary rates of loading as shown in Table I, which is taken from tests by one of the authors**(179)**.

Hopkinson and Rogers**(55)** reported that as the temperature rose the stress-strain relations in steel underwent remarkable changes which might best be expressed by saying that the variously called "creeping," or "*elastiche nachwirkung*," or "time-effect," increased greatly with temperature. While such effects might be detected at ordinary temperatures they attained a different order of magnitude at red heat, 1100° F. (600° C.). The effect of "creeping" was found to make the determination of Young's modulus a matter of some uncertainty for the extension of a bar stressed at 1110° F. (600° C.)

varied 15 per cent or more depending on the time of application of load. For very short applications of the order of one or two seconds, the strain produced approached a definite limiting value which, if used in determination of the modulus, made it independent of the manner of loading and a physical constant.

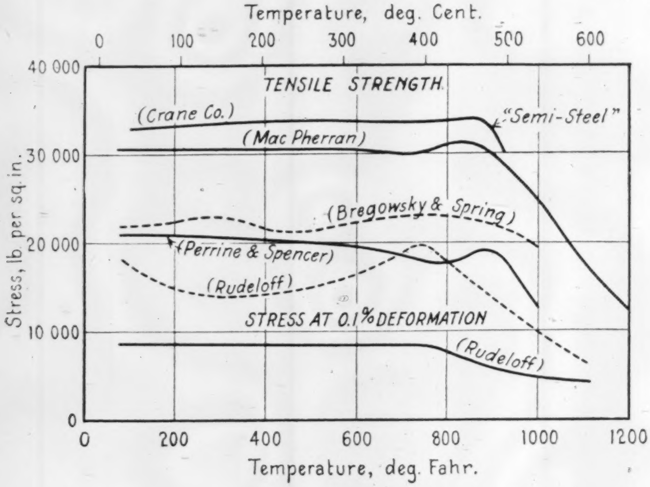

FIG 1.—High-Temperature Tensile Properties of Cast Irons and Semi-Steel as Reported by Various Investigators.

Investigator	Bibliography Reference No.	Chemical Composition, per cent							Remarks
		Combined Carbon	Graphitic Carbon	Total Carbon	Mn.	Si	P	S	
MacPherran...	(128)	....	....	....	0.64	1.84	0.52	0.11	Annealed at 1100° F. (595° C.) before test.
Bregowsky and Spring......	(63)	0.17	3.31	....	0.60	2.57	0.73	0.10	
Perrine and Spencer.....	(75)	....	....	2.69	....	....	....	....	Curve based on very few tests.
Rudeloff[a]......	(25)	....	....	3.56	0.93	2.64	0.52	0.05	Curves are averages from both wet and dry sand castings.
Crane Co.....	(148)	"Semi-steel" or "ferro-steel"				......	......	......	In reality a low-carbon cast iron with high Mn and low Si.

[a] 1000 lb. per sq. in. = 0.7031 kg. per sq. mm.

Many other tests including those of Robin(71) and more recently Chevenard(124) and Dickenson(172) throw light upon the time effect and its importance in any discussion of the high-temperature properties of metals.

Under the conditions outlined it should therefore be recognized that terms such as "proportional limit," "yield point," "tensile strength," etc., which are used in this report, represent values obtained in each case under given conditions of test and do not necessarily have the same significance throughout a large part of the temperature range considered as in tests at room temperatures.

TENSION TESTS

Cast Irons, Semi-Steel and Malleable Iron.—The results of tension tests reported by a number of investigators for cast irons, semi-steel and malleable iron are shown graphically in Figs. 1 and 2. The discrepancies in numerical values for the various irons, which are not in all cases completely identified, is relatively unimportant for the moment. The principal feature to be observed for the three types of product is the small change in tensile properties with temperature rise from 70 to about 800° F. (20 to 425° C.). There are some indications of a maximum in the tensile strength - temperature curves at about 600 to 800° F. (315 to 425° C.), but this is smaller than in the case of carbon steels and for most practical purposes the tensile values may be considered nearly constant throughout the specified range. With further increase in temperature there begins a "softening" which becomes quite rapid above about 900° F. (480° C.).

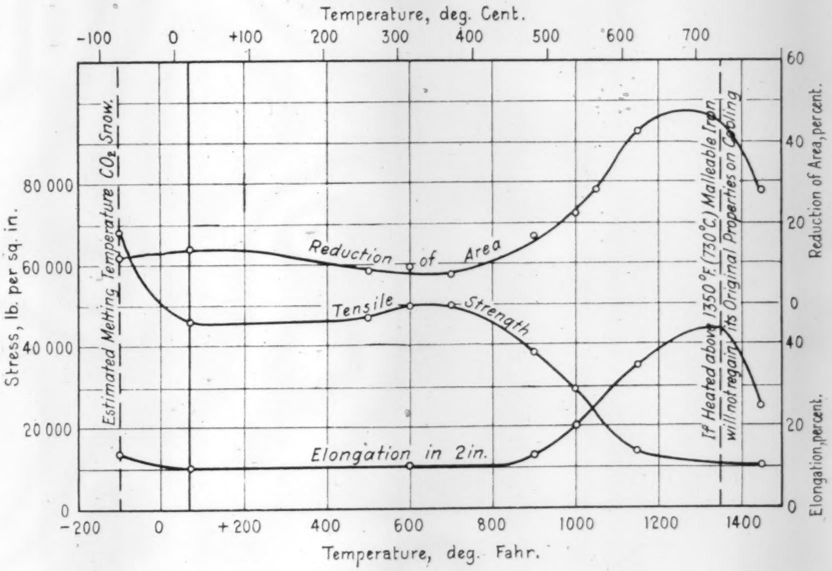

FIG. 2.—Tensile Properties of Malleable Cast Iron at Various Temperatures [Schwartz (131)].

Tests made on specimens 0.634 in. in diameter, ground to size before annealing. The results are known, according to Schwartz, to be unaffected by shrinkage or other defects.

Decrease below 70° F. (20° C.) results in a "stiffening" of the metal as shown by increased tensile strength and some decrease in elongation and reduction of area in the case of malleable iron. In general the effect is accompanied by increased brittleness.

Wrought Iron and Mechanically Worked Steels.—By far the largest number of tests in tension have been made on mechanically worked steels with or without subsequent thermal treatments. Many interesting comparisons are possible but it is impracticable to include in this report more than a brief summary of features having very general interest and to reproduce data for more than a few steel types.

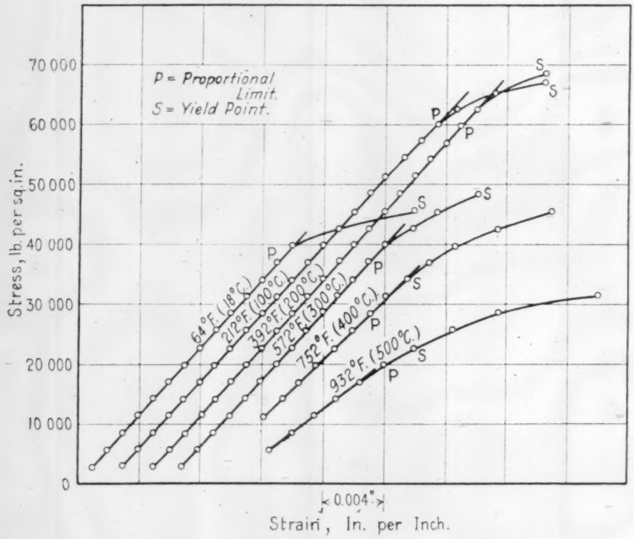

FIG. 3.—Effect of Temperature on the Stress-Strain Relations in Tension of 0.37-per-cent Carbon Steel [Welter (164)].

NOTE.—1000 lb. per sq. in. = 0.7031 kg. per sq. mm.

Figs. 3 to 8, inclusive, show the effect of temperature variations upon the proportional limit, tensile strength, elongation, reduction of area, and the stress-strain relations, including the modulus of elasticity, of carbon and some alloy steels.[1] While an attempt has been made to choose representative results for these graphs it should be kept in mind that they are based on tests of individual heats under specific test conditions. Variations in numerical values may be expected when comparing tests of additional heats of the same type in one laboratory or of the same heat in different laboratories.

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[1] Graphs are not given for wrought iron as the changes in properties are quite similar to those shown for low-carbon steels.

Some of the important facts, which may be deduced from available results of a large number of similar tests, may be summarized as follows:

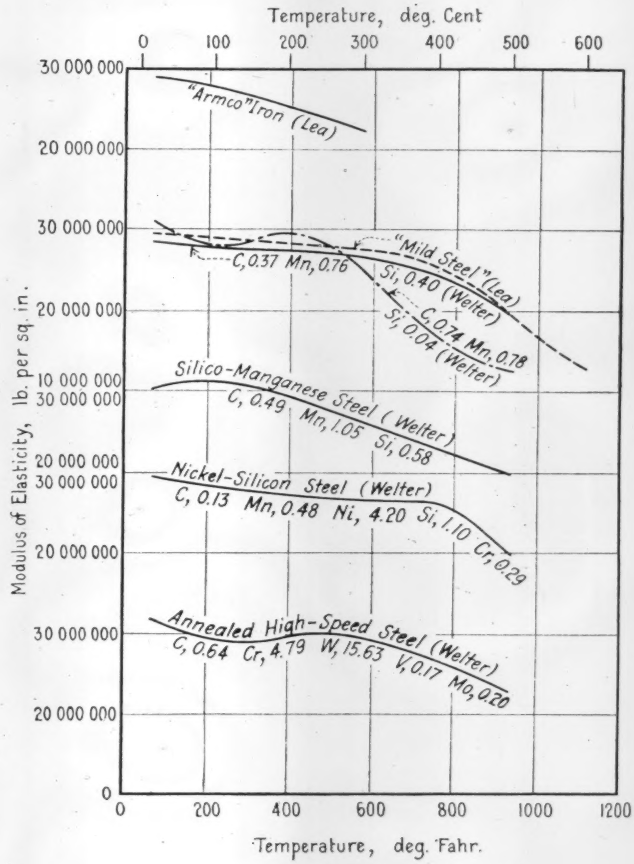

FIG. 4.—Effect of Temperature on the Elastic Modulus of Various Steels in Tension.
The work of Welter is given in item (**164**) of the bibliography; that of Lea in items (**103**) and (**187**).

1. The effect of temperature rise to about 1100° F. (600° C.) is to reduce tensile strength, proportional limit and the elastic modulus and greatly increase ductility and the tendency to creep in wrought iron and steels. Certain combinations of composition and treatment, notably normalized chromium-

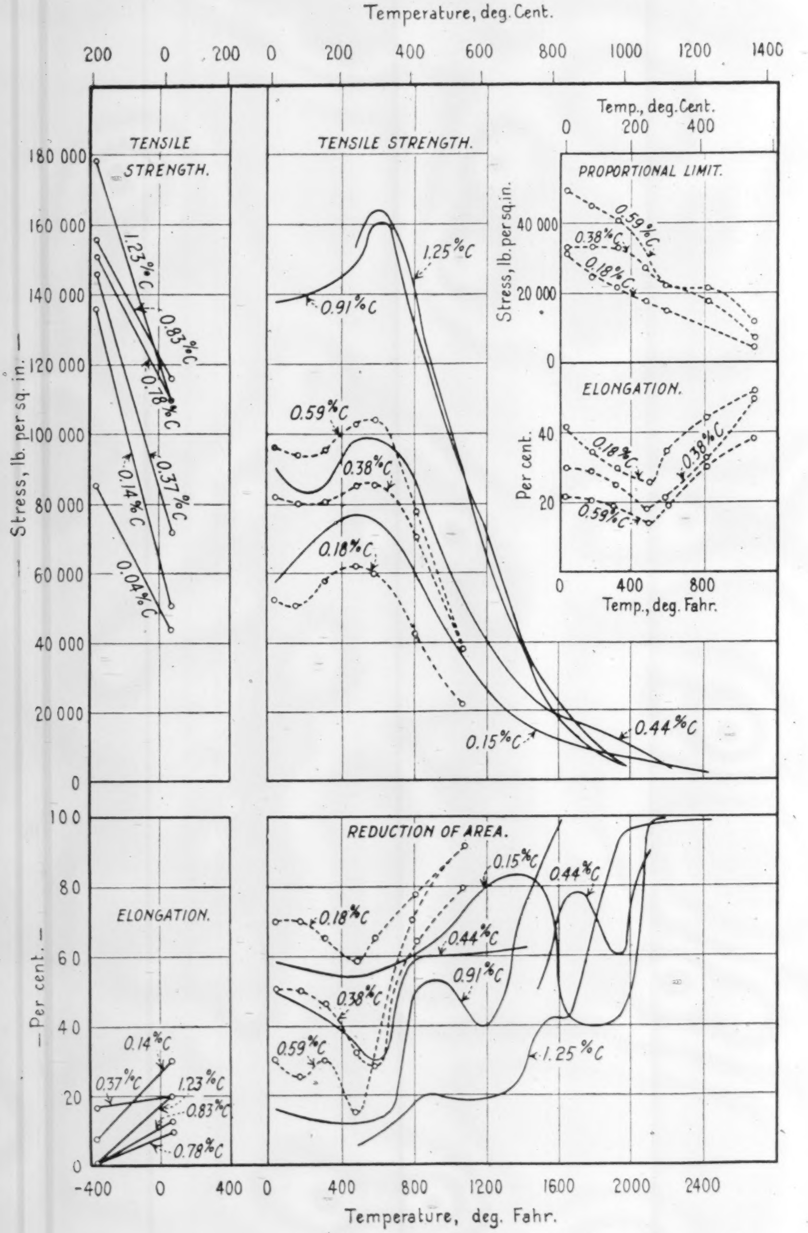

FIG. 5.—Effect of Temperature on the Tensile Properties of Carbon Steels as Determined by Various Investigators.

Solid lines at elevated temperatures are results reported by Dupuy (**150**) for normalized steels; dotted lines are results on normalized steels obtained by the authors (**196**). Results below room temperature are those reported by Hadfield (**54**) for annealed steels containing about 0.1 to 0.3 per cent of manganese.

vanadium, quenched-and-tempered stainless and air-cooled 28-per-cent nickel steels are strongest at ordinary temperatures,

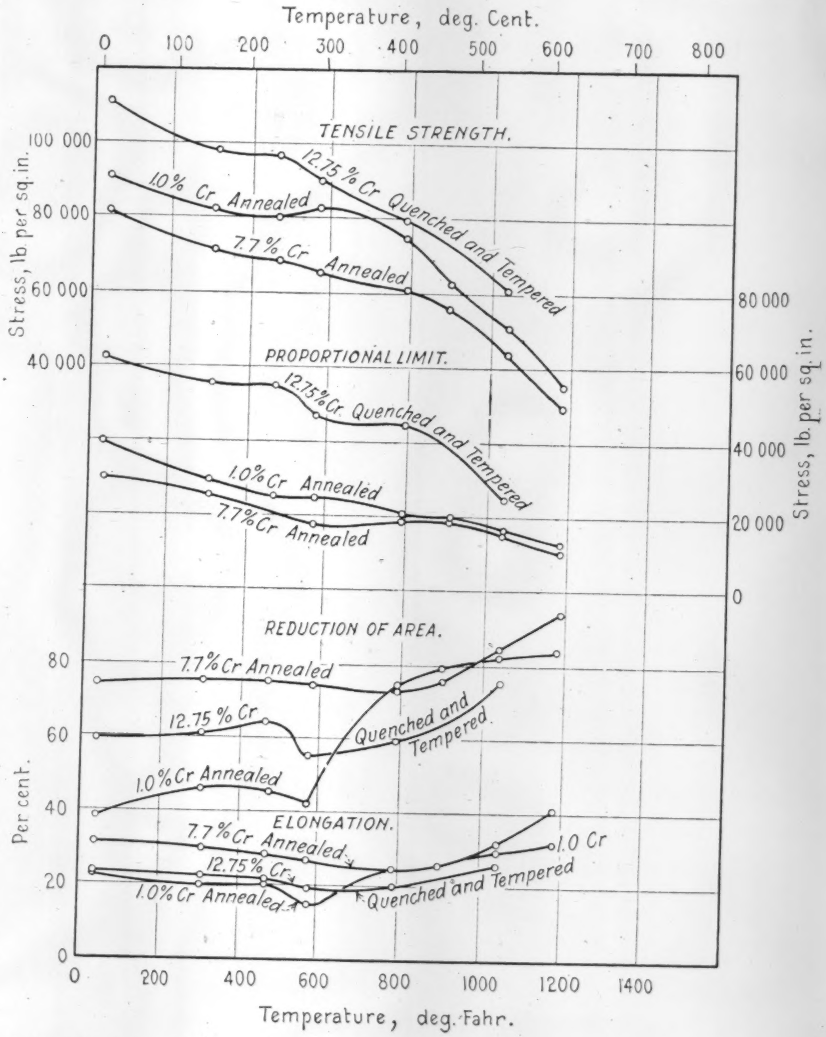

FIG. 6.—Effect of Temperature on the Tensile Properties of Various Chromium Steels Containing 0.3 to 0.4 per cent of Carbon. (Tests by the Authors.)

Annealed = Annealed by heating for 45 min. at 1650° F. (900° C.) and furnace cooling.

Quenched-and-Tempered = Oil quenched from 1750° F. (955° C.); then tempered 45 min. at 1250° F. (675° C.) and air cooled.

but carbon and the majority of alloy steels show maximum tensile strength values and minimum ductility in the range of 400 to 650° F. (205 to 350° C.).

2. The proportional limit of medium or low-carbon steel, which has been largely relieved of stress by suitable treatment decreases with rise in temperature. In highly stressed metal, resulting from cold or blue-work or quenching and that having residual stress, such as often exists in thin sections of hot-finished steel, the proportional limit either remains at approximately its room-temperature value over a well-defined interval or shows an increase with first rise in temperature.

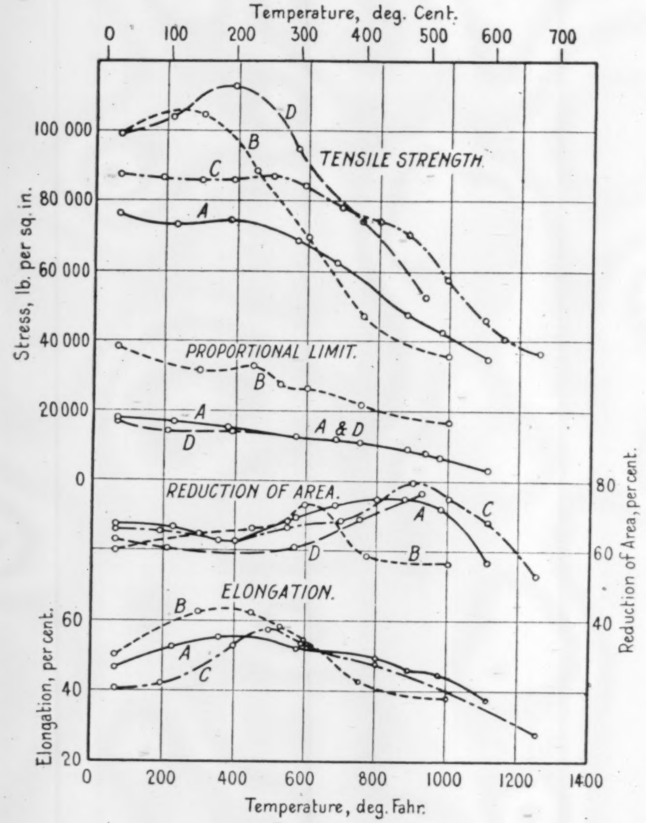

Fig. 7.—Effect of Temperature on the Tensile Properties of Steels Containing from 25 to 35 per cent Nickel as Determined by Various Investigators.

A = 28-per-cent nickel steel reported by French (**196**); first air cooled from 1475° F. (800° C.).

B = 31-per-cent nickel steel reported by Bregowsky and Spring (**83**); tested in condition "as received."

C = 34-per-cent nickel steel reported by MacPherran (**158**); tested as forged.

D = 25-per-cent nickel steel reported by Welter (**164**).

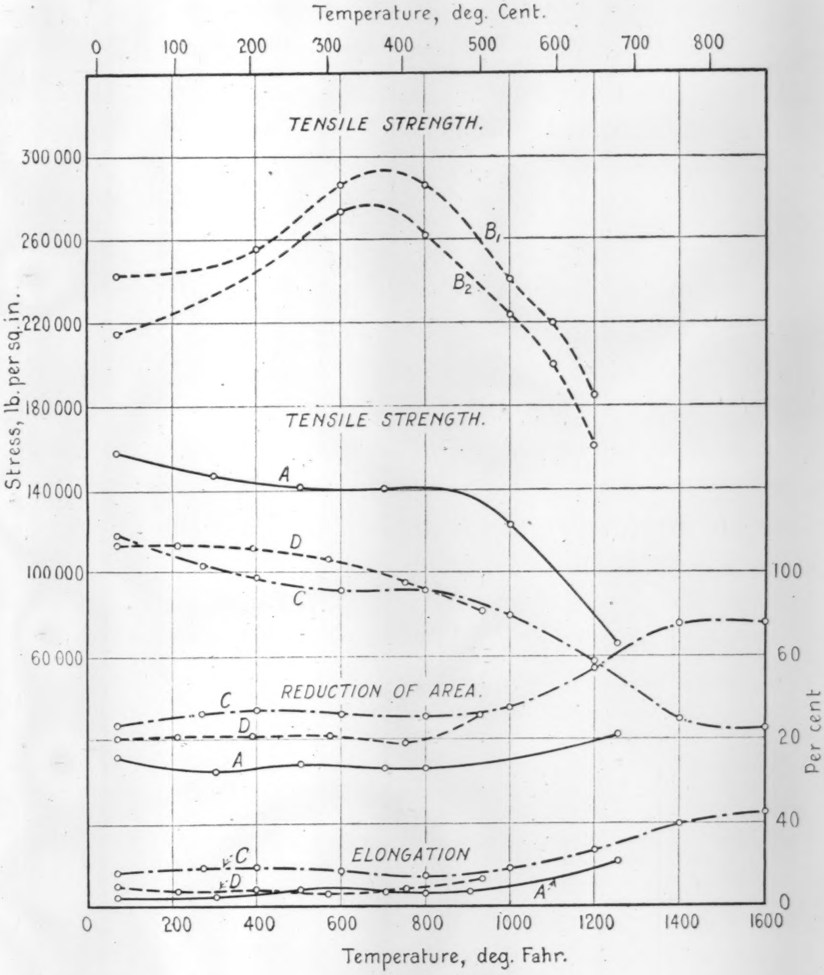

FIG. 8.—High-Temperature Tensile Properties of Annealed or Quenched-and-Tempered High-Speed Steels Reported by Various Investigators.

	Investigator and Reference	Type Composition, per cent				Preliminary Treatment
		C	Cr	W	V	
A	MacPherran (**158**)	0.68	3.36	19.3	0.88	2300° F. (1260° C.) oil; tempered 1400° F. (760° C.)
B_1	d'Arcambal (**148**)	0.65	3.62	17.8	0.95	2350° F. (1290° C.) oil; tempered 1100° F. (595° C.)
B_2	d'Arcambal (**148**)	0.69	3.13	13.9	1.68	2350° F. (1290° C.) oil; tempered 1100° F. (595° C.)
C	Spooner (**162**)	0.66	3.15	15.9	0.70	Annealed at 1660° F. (905° C.)
D	Welter (**164**)	0.64	4.79	15.6	0.17	"Annealed"

3. From the standpoint of high strength and limit of proportionality of steels at elevated temperatures, the temperature scale may be divided roughly into three parts: (1) the range 70 to about 850° F. (20 to 450° C.); (2) the range 850 to 1100° F. (450 to 600° C.); (3) above about 1100° F. (600° C.).

4. In the lowest range, high strength and proportional limit are functions of composition and heat treatment and in general combinations giving highest strength at ordinary temperatures show similar superiority throughout the entire range. It is, however, advisable to keep the carbon low since decreased ductility becomes more marked with increase in carbon content, particularly in the blue-heat range.

5. The upper limit in the second or "transition" range requires nearly full tempering following hardening for stability, so that in most cases the benefits to be derived from heat treatment are limited (except in the lower portion of the range) and high strength and limit of proportionality are more largely functions of composition. While short-time tests reported do not give quantitative comparisons for steels subjected to sustained loads, on account of the importance of the time factor, it would be reasonably expected that steels having highest limits of proportionality would be able to sustain higher loads than those with low proportional limits though not necessarily in direct proportion to observed values. On this basis of comparison it appears possible to improve the properties of steel by adding such elements as chromium, cobalt, uranium, molybdenum and vanadium.

6. The drop in strength and proportional limit of steels at temperatures around 1025° F. (550° C.) is permanent for most practical purposes, so that it would appear improbable that commercial steels can be produced to withstand continuously, fairly large loads at temperatures above about 1200° F. (650° C.) except when large proportions of one or more alloying elements are added to reduce the iron content to such a low value that the resulting product cannot correctly be called steel, or in special cases where extremely large proportions of special compounds are present.

Cast Steels.—In general, the effect of temperature increase on the mechanical properties of cast steels is similar to that on mechanically worked steels. However, the actual values obtained in tests will differ materially up to about 800 to 1000° F. (425 to 540° C.) and to a somewhat less extent at higher temperatures from those values observed in similar steels after mechanical work. As both chemical and physical characteristics play a predominant part at slightly elevated temperatures in the latter class of steels, so will these same factors, as reflected in the details of casting practice and heat treat-

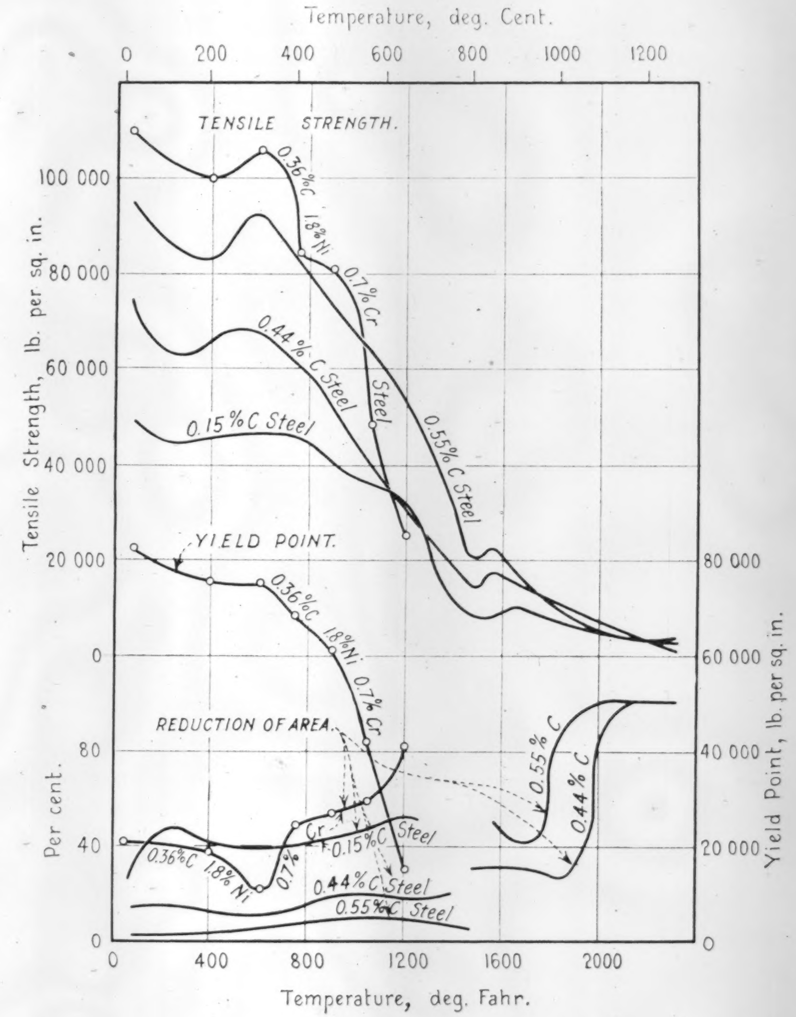

FIG. 9.—Effect of Temperature on the Tensile Properties of Cast Steels (Various Investigators).

Results on carbon steels are those reported by Dupuy (**150**); those for the nickel-chromium steel were obtained from V. T. Malcolm, Chapman Valve Manufacturing Co.

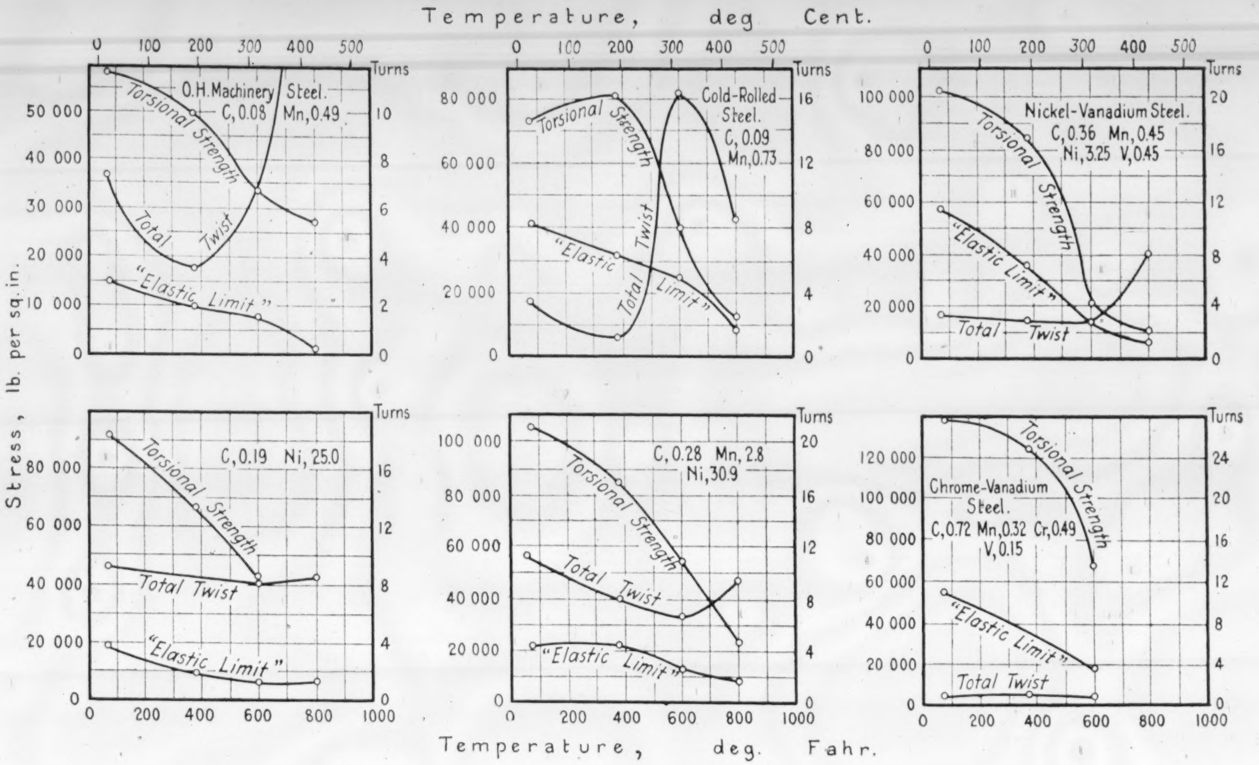

FIG. 10.—Effect of Temperature on the Torsional Properties of Various Steels [Bregowsky and Spring (83)].

"Elastic limits" determined from stress-strain relations obtained with a troptometer. Specimens had 8-in. gage length and were 0.855-in. in diameter, except the 30-per-cent nickel steel which was 1 in. in diameter. All tests made on material as received.

ment, be of prime importance in determining the properties observed in cast metals. They are, of course, to be considered of importance at all temperatures but the weakening effect on all alloys containing large proportions of iron becomes so marked when the temperature becomes high that it obscures, at least in large part, the differences referred to. Representative results obtained on cast carbon and nickel-chromium steels are shown graphically in Fig. 9 and in view of the previous discussions no further comments will be added.

TORSION TESTS

Very little has been published concerning the torsional properties of ferrous metals at various temperatures. The report of Bregowsky and Spring(**83**) is the only one that has so far come to the authors' attention giving results in the range 70 to 800° F. (20 to 425° C.) and some of the results are reproduced in Fig. 10. While insufficient data are given from which to draw general conclusions, a marked "softening" is observed in all steels tested when the temperature is raised from that of the room to 800° F. (425° C.). However, there appears to be a range of minimum ductility in the neighborhood of 400 to 600° F. (205 to 315° C.) as shown by the small number of turns (twists) before failure. This coincides quite closely with minimum values of elongation and reduction of area observed in tension tests of similar materials.

While considering the torsional properties of ferrous metals attention should be drawn to the qualitative experiments described by Brearley[1] to show the effects upon steels of temperatures in the neighborhood of those used in hot working. A bar of steel, either rectangular or appropriately marked so that the twisting could readily be followed, was heated to about 1800 to 2000° F. (1000 to 1100° C.) at one end and then removed from the furnace to allow the heat to taper down until, within 3 or 4 in. from the colder end, it was at perhaps 1100° F. (600° C.). The hot end was then placed in a vise and the bar twisted from the colder end. In nearly all cases there was a twist of short pitch at the hottest end; then somewhere down the metal at intermediate temperatures came a twist of longer pitch and finally there was a twist of shortest pitch where the metal was coldest.

Very recently similar experiments were carried out more carefully by Sauveur(**150**) who found that such discontinuities in the twist were associated with an independent A_3 transformation; hence they were observed in iron or steels containing less than about 0.40 per cent carbon. This temperature range within which a "critical twist" was observed may be called a zone of "reduced malleability" and coincides with the so-called "hot-short" range long recognized by mill men for the very pure iron known as Armco or ingot iron. Discontinuities in mechanical properties – temperature curves in this range have also been shown in tension tests by Rosenhain(69) and others.

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[1] Discussion of report by Dickenson (**172**).

HARDNESS TESTS

Hardness tests, using the Brinell method, have been reported by Brinell(53), Kürth(62), Robin(63) and Ito(198), etc. As shown in Fig. 11, the hardness decreases progressively with temperature rise from −80 to 2200° F. (−60 to 1200° C.) with the exception of a fairly narrow temperature range around "blue heat" where a rise in temperature results in an increase in hardness. This effect is observed between 400 and 600° F. (205 and 315° C.) in the hardness-temperature curves of Kürth for carbon steels and coincides with the zone of minimum ductility or maximum strength shown in most tension and torsion tests of similar alloys; in the case of Brinell's curves it extends over a wider range and occurs at somewhat higher temperatures.

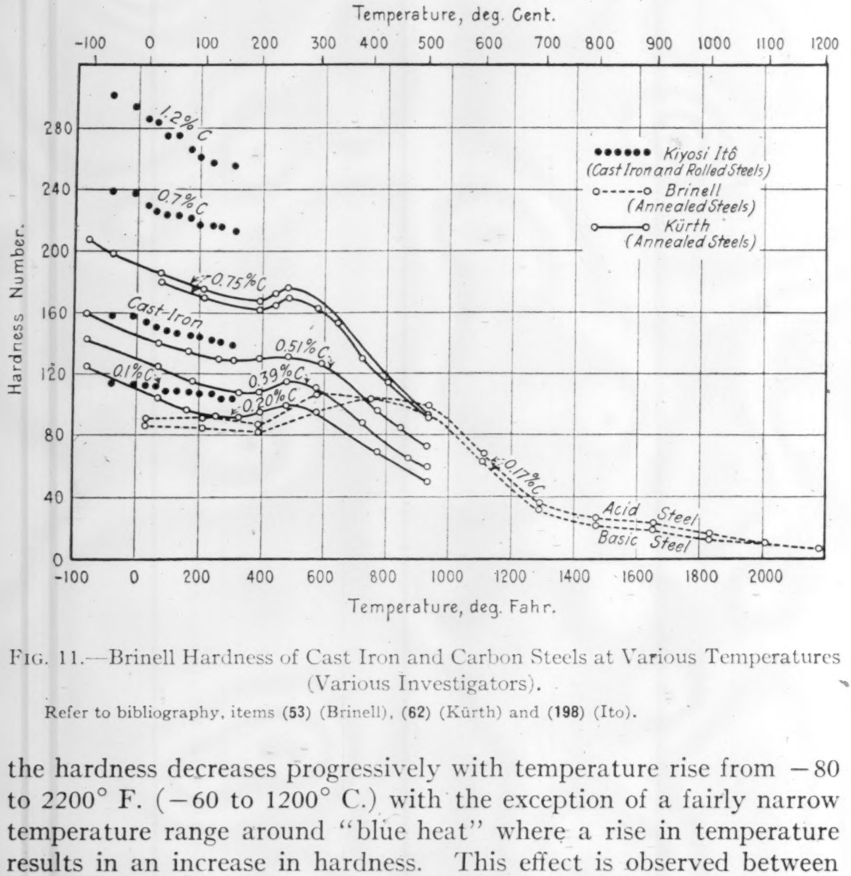

FIG. 11.—Brinell Hardness of Cast Iron and Carbon Steels at Various Temperatures (Various Investigators).

Refer to bibliography, items (53) (Brinell), (62) (Kürth) and (198) (Ito).

CRUSHING TESTS

What may be called the "deformational characteristics" of irons and steels have been very carefully studied throughout a wide temperature range by Robin (71). The extent of his investigations prevents a complete summary but there are a number of features relating particularly to crushing tests and comparisons of crushing resistance with other mechanical properties which should be referred to in some detail. Among these are the following:

"The work necessary to effect a given crushing varies according to the number of blows of a given intensity which produced this crushing. The curves of crushing or of the resistance to crushing, in terms of the number of blows, are hyperbolic and depend on the hardness and on the elasticity of the metal. The direction of the curves changes when the heat diminishes the resistance of the metal, whereupon the latter behaves like a soft metal."

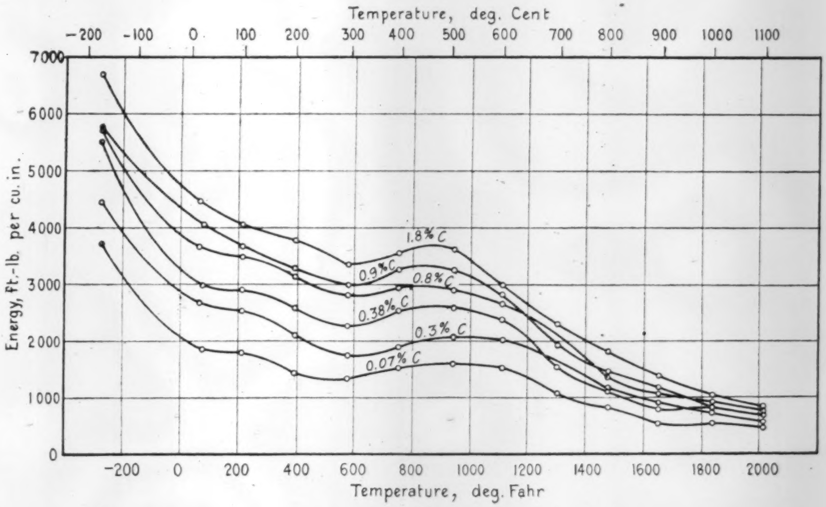

FIG. 12.—Loads Required at Various Temperatures to Reduce the Height of Rolled Carbon-Steel Cylinders (With Ratio of Length to Diameter of 1) by 20 per cent When the Force is Applied at 6.56 ft. (2 meters) per second [Robin (71)].

"The resistance to crushing of a straight steel with circular base diminishes when the ratio of its depth to the diameter of its base increases. The law which correlates this resistance with the relative dimensions of cylinders is represented graphically by the hyperbolic paraboloid. In cylinders with constant dimensions of the base and with increasing depths the resistance to crushing diminishes hyperbolically; in cylinders of constant depth but increasing diameter, the resistance to crushing increases in proportion."

"The rate of testing influences the resistance of metals to crushing. As in the case of a number of different blows it acts in opposite ways according as it is a question of hard and elastic metals or soft metals. At each temperature of crush in any metal the rate of speed produces specific variations in the numerical results."

"The resistance to crushing (of carbon steels) which is relatively considerable at liquid air temperatures, −310° F. (−190° C.) diminishes very rapidly up to 30° F. (0° C.) and then slowly up to 570° F. (300° C.) where the minimum resistance is found. The resistance increases reaching a maximum at about 930° F. (500° C.) followed by a rapid fall at 1560° F. (850° C.) and a very slow fall at higher temperatures. [Refer to Fig. 12.] Lack of cohesion in steels containing high percentages of carbon and the intervention of fusion in soft steels restrict the experiments reducing the resistance to crushing to an exceedingly low value."

Robin further pointed out that "interstrained" steels give more marked variations in crushing resistance than do the same steels after annealing; on the other hand, phosphorus diminishes the variations but "increases the value in common, generally speaking, with other elements dissolved in iron."

"Pearlitic steels undergo the same variations as carbon steels; variations in resistance to crushing may be greatly reduced or even obliterated by the presence of a sufficient amount of an element in solution, such for example, as chromium.

"Martensitic steels yield a decreasing curve which possesses neither maximum nor minimum; the greatest fall in resistance commences at 930° F. (500° C.).

"Austenitic steels vary little in their resistance to crushing up to about 1000 or 1100° F. (550 or 600° C.). The resistance to crushing increases considerably at liquid-air temperatures. Starting from 30° F. (0° C.), the curve is generally rectilinear up to about 1110° F. (600° C.) where the most important fall in resistance occurs. Special steels containing the free carbide and the high-speed steels investigated behave similarly. Their resistance at ordinary temperatures and particularly at about −310° F. (−190° C.) is, generally speaking, high. Some steels preserve a high degree of resistance to crushing at high temperatures, a resistance much greater than that of carbon steels. The presence of nickel favors this resistance at high temperatures."

In comparing the static and dynamic tests of steels at various temperatures, Robin pointed out that:

"The static tensile and hardness tests correspond with one another. Compression appears to indicate corresponding variations: the rate of testing affects the observed results at higher temperatures up to a limit which apparently cannot in practice be exceeded and relates to shocks of any rate or intensity whatever. Brittleness as the result of static effects appears to occur at 570° F. (300° C.) but brittleness under shock is practically in the neighborhood of 930° F. (500° C.).

"The properties of steel, so far as the dynamic and static effects are concerned, vary in totally different ways according to the temperature and according to the nature of the steels. The correlation of these effects at the normal temperature in the case of certain steels appears, therefore, to be due purely to coincidence."

IMPACT TESTS

The results obtained by Reinhold(**113**), Charpy(**97**), Guillet(**59**) and more recently Langenberg(**200, 201**) will serve to show the effects of temperature variations upon the impact resistance of steels as determined on notched bars. Representative results are shown graphically in Figs. 13 and 14.

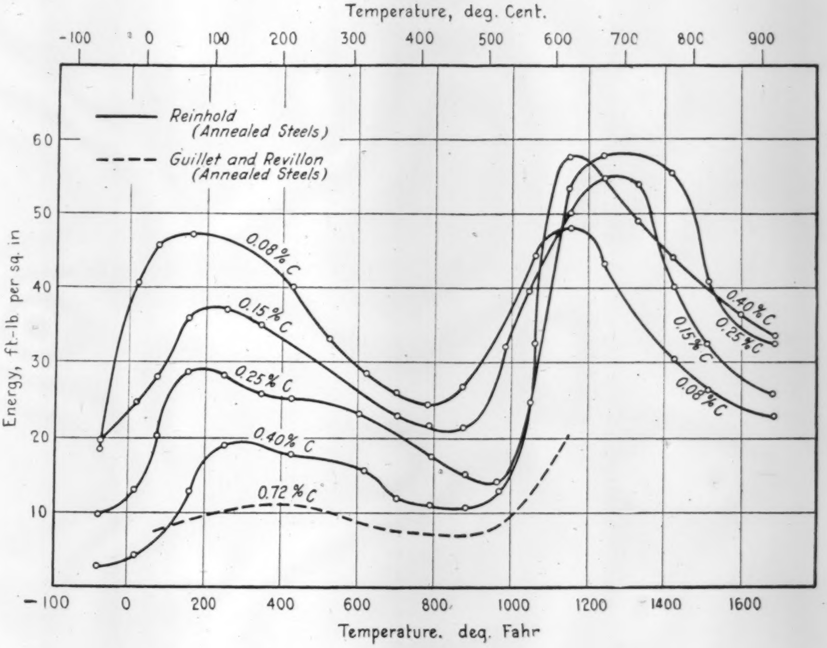

FIG. 13.—Notched-Bar Impact Resistance of Carbon Steels at Various Temperatures.

Refer to bibliography, items (**59**) [Guillet and Revillon (Guillery test)] and (**113**) [Reinhold (Charpy test)]

The general form of the impact energy-temperature curves is quite similar for the majority of steels tested. As the temperature is progressively raised from about −100° F. (−75° C.) the absorbed energy increases and reaches maximum values in the range 150 to 400° F. (65 to 205° C.); it then decreases. According to the results obtained by Reinhold, Guillet and Charpy, a second rise in impact resistance begins in the neighborhood of 800 to 1000° F. (425 to

540° C.) and is followed by maximum values which in general are greater than the first maximum between 150 and 400° F. (65 and 205° C.). As the temperature is raised above about 1200 to 1400° F. (650 to 760° C.) the absorbed energy decreases rapidly.

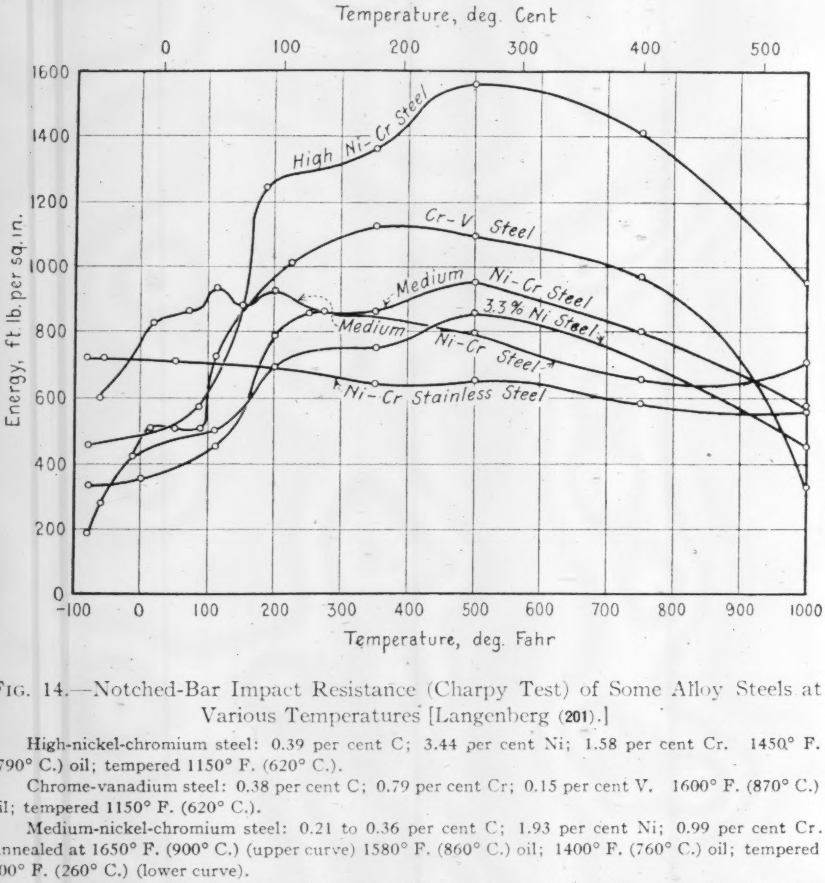

Fig. 14.—Notched-Bar Impact Resistance (Charpy Test) of Some Alloy Steels at Various Temperatures [Langenberg (201).]

High-nickel-chromium steel: 0.39 per cent C; 3.44 per cent Ni; 1.58 per cent Cr. 1450° F. (790° C.) oil; tempered 1150° F. (620° C.).

Chrome-vanadium steel: 0.38 per cent C; 0.79 per cent Cr; 0.15 per cent V. 1600° F. (870° C.) oil; tempered 1150° F. (620° C.).

Medium-nickel-chromium steel: 0.21 to 0.36 per cent C; 1.93 per cent Ni; 0.99 per cent Cr. Annealed at 1650° F. (900° C.) (upper curve) 1580° F. (860° C.) oil; 1400° F. (760° C.) oil; tempered 500° F. (260° C.) (lower curve).

Nickel-Chromium stainless steel: 0.38 per cent C; 23.75 per cent Ni; 7.08 per cent Cr. Annealed at 1290° F. (700° C.).

3.30-per-cent nickel steel: 0.31 per cent C; 3.30 per cent Ni. 1515° F. (825° C.) oil; tempered 1110° F. (600° C.).

These changes appear to be quite generally characteristic of the majority of steels for which data are available, but the magnitude of the observed effects is dependent to a large degree upon composition, previous mechanical and thermal treatments and upon the methods used in the test. The most notable exception is the high nickel-chromium steel containing also about 1.5 per cent silicon, tested by

Langenberg. In this case the absorbed energy shows a very gradual and comparatively small decrease as the temperature is raised from −80 to 1000° F. (−60 to 540° C.).

Attention has already been called to the low ductility in steels in the neighborhood of "blue heat" (400 to 600° F.) (205 to 315° C.) as shown in both tension and torsion tests. This effect is apparently distinct from and not accompanied by brittleness, as the energy absorbed in the notched bar impact tests does not show low values in the specified temperature range.

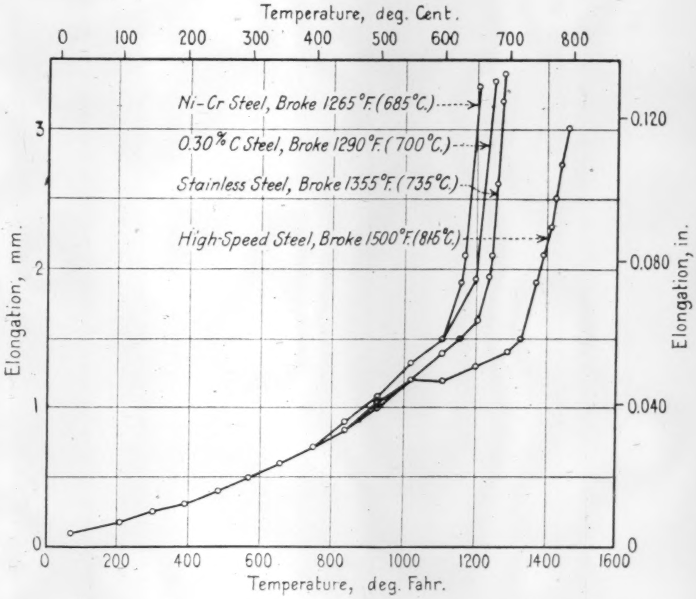

FIG. 15.—"Flow" of Various Steels Under a Static Load of 19,000 lb. per sq. in. (8.5 tons per sq. in.) with Rising Temperature [Dickenson (172).]

Composition and treatment of the various steels are given in Table II.

Langenberg has pointed out and special consideration should be given to the marked influence on impact resistance of ordinary atmospheric temperature variations. Also steels and treatments giving highest impact resistance at 70° F. (20° C.) do not necessarily show the same degree of superiority at higher or lower temperatures and in quite a number of cases the order is reversed. A similar condition is observed in the short-time tension tests and shows the need for readjustment in methods of design of equipment for high or low temperature service.

Another feature of special interest is the superior resistance to impact of the commercial nickel-chromium steels compared to $3\frac{1}{2}$-per-cent nickel steel and likewise the superiority of chromium or chromium-vanadium steels compared to nickel-chromium steel.

The available impact tests show, among other things, that chromium is highly beneficial in the quantities ordinarily used and in comparison with the other alloying elements at present employed in commercial steels appears to "toughen" as well as "stiffen" the resulting metal in those temperature ranges in which composition is of prime importance as compared to heat treatment.

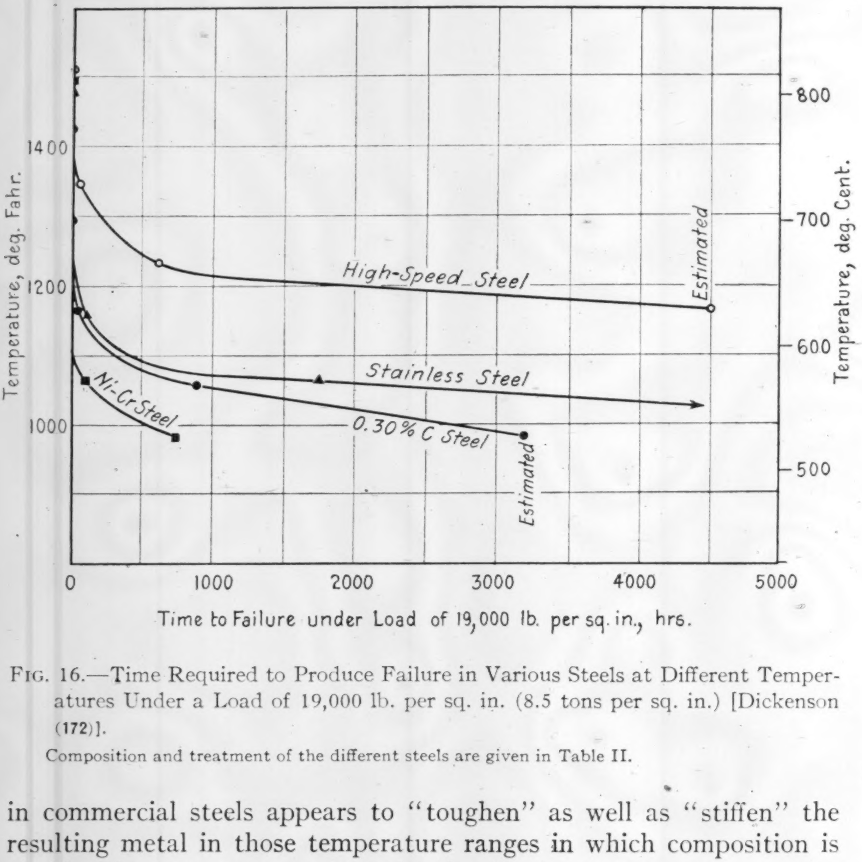

FIG. 16.—Time Required to Produce Failure in Various Steels at Different Temperatures Under a Load of 19,000 lb. per sq. in. (8.5 tons per sq. in.) [Dickenson (172)].

Composition and treatment of the different steels are given in Table II.

LONG-TIME OR "FLOW" TESTS

Mention has already been made in this report of the importance of the time factor in testing metals at high temperatures. In 1919, Chevenard(124) published results obtained under sustained loading on an air-hardening nickel-chromium steel and among other things gave

TABLE II.—LIMITING TEMPERATURES SET BY DICKENSON (172) AT WHICH A LOAD OF 19,000 LB. PER SQ. IN. CAN BE SUSTAINED IN BOTH SHORT AND LONG-TIME TENSION TESTS.

Type of Steel	Heat Treatment[a]	Maximum Temperature to which Steel will withstand Stress of 19,000 lb. per sq. in.			
		For Short Duration of Loading[b]		For Considerable Time without Sensible Deformation	
		deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.
0.30-per-cent carbon steel	1560° F. (850° C.) oil; tempered at 1065° F. (575° C.)	1425	775	930	500
0.45-per-cent carbon steel	1600° F. (870° C.) water; tempered at 1110° F. (600° C.)	1480	805	840	450
Nickel-chromium steel, 0.25 per cent C; 3.6 per cent Ni; 0.6 per cent Cr	1525° F. (830° C.) oil; tempered at 1110° F. (600° C.)	1470	800	970	520
Stainless steel, 0.26 per cent C; 14.7 per cent Cr; 0.6 per cent Si; 0.4 per cent Ni	1700° F. (925° C.) oil; tempered at 1200° F. (650° C.)	1650	900	1065	575
High-speed steel, 0.6 per cent C; 17.4 per cent W; 4.0 per cent Cr; 0.7 per cent V	Annealed 1470° F. (800° C.)	1770	965	1110	600

[a] Fahrenheit temperatures given to nearest 5° in conversion from Centigrade scale.
[b] This refers to the tensile strength values.

TABLE III.—COMPARISON OF SOME DATA IN BOTH LONG AND SHORT-TIME TENSION TESTS AT HIGH TEMPERATURES.

Steel	Heat Treatment[a]	Temperature	
		deg. Fahr.	deg. Cent.
MAXIMUM TEMPERATURE AT WHICH STEEL WILL SUSTAIN A STRESS OF 19,000 LB. PER SQ. IN. FOR LONG PERIODS WITHOUT SENSIBLE FLOW[a]			
0.30-per-cent carbon steel	1560° F. (850° C.) oil; tempered 1065° F. (575° C.)	930[b]	500[b]
0.45-per-cent carbon steel	1600° F. (870° C.) water; tempered 1110° F. (600° C.)	840[b]	450[b]
Nickel-chromium steel, 0.25 per cent C; 3.6 per cent Ni; 0.6 per cent Cr	1525° F. (830° C.) oil; tempered 1110° F. (600° C.)	970[b]	520[b]
Stainless steel, 0.26 per cent C; 14.7 per cent Cr; 0.6 per cent Si; 0.4 per cent Ni	1700° F. (925° C.) oil; tempered 1200° F. (650° C.)	1065[b]	575[b]
High-speed steel, 0.6 per cent C; 17.4 per cent W; 4.0 per cent Cr; 0.7 per cent V	Annealed 1470° F. (800° C.)	1110[b]	600[b]
TEMPERATURE AT WHICH A PROPORTIONAL LIMIT OF 19,000 LB. PER SQ. IN. IS SHOWN IN THE SHORT-TIME TENSILE TEST[a]			
0.33-per-cent carbon steel	1555° F. (845° C.) water; tempered 1005° F. (540° C.)	790[c]	420[c]
Nickel-chromium steel, 0.39 per cent C; 3.1 per cent Ni; 0.9 per cent Cr	Air cooled from 1560° F. (850° C.)	930[d]	500[d]
Stainless steel, 0.31 per cent C; 12.8 per cent Cr	1750° F. (955° C.) oil; tempered 1210° F. (655° C.)	1065[e]	575[e]
High-speed steel, 0.64 per cent C; 15.6 per cent W; 4.8 per cent Cr; 0.2 per cent V; 0.2 per cent Mo	Annealed	860[f]	460[f]

[a] Fahrenheit temperatures given to nearest 5° in conversion from Centigrade scale.
[b] From data reported by Dickenson (**172**).
[c] From data obtained by one of the authors.
[d] From data reported by French (**153**).
[e] From data reported by French (**180**).
[f] From data reported by Welter (**164**).

definite values for the rate of flow for various loads at different temperatures. More recently Dickenson(172), following the same principles, reported results obtained in both short-time and prolonged tension tests of various steels. Two carbon steels, a nickel-chromium steel, stainless (13 per cent chromium) and high-speed steels were investigated and results are reproduced in part in Figs. 15 and 16.

Table II is also taken from Dickenson's report and shows quite clearly that the ordinary tensile strength values at high temperatures give no direct indication either of the limiting temperatures up to which fixed loads can be maintained without sensible flow or the limiting loads which can be sustained at various temperatures.

While freely condemning the short-time tension test as being worthless for use by designing engineers, Dickenson unfortunately neglected the only factors which might show a direct relation to the results obtained so laboriously in the long-time tests. No attempt was made to determine proportional or elastic limits and the stress-strain relations in the ordinary tests or to correlate existing data of this type with the limiting values determined under prolonged loading.

In Table III are given the limiting temperatures determined by Dickenson at which a load of 19,000 lb. per sq. in. (8.5 tons per sq. in.) can be sustained for long periods by each of the five steels without sensible deformation, and also the temperature at which a proportional elastic limit of 19,000 lb. per sq. in. is shown in the short-time tension test. These latter values were, of necessity, collected from various sources so that many variables are introduced when comparisons are attempted, such as, for example, individual heat characteristics of the steels, variations in chemical composition and heat treatment, methods of test, etc. Despite these variations the limiting temperatures determined from the stress-strain relations in the short-time tests are comparable to those deduced from the prolonged loading. In fact in all but one case the former values are somewhat lower than the latter. For the two stainless steels which are quite similar in composition and heat treatment identical values are obtained.

It is not intended to give the impression that proportional limits determined by methods so far employed can give as accurately as sustained-loading tests the limiting loads or temperatures for various steels, but at least the comparisons cited point to the possibility of obtaining from the stress-strain relations in a short-time test with slow rates of loading quite satisfactory information for most practical purposes. Dickenson's values may be accepted as quite accurate, but it should be kept in mind that they are based on individual heats tested under specific conditions. Similar tests carried out on additional heats of each type of steel would undoubtedly show variations which might possibly be as great as the differences shown by the two methods in Table III.

SPECIAL HIGH-TEMPERATURE PROPERTIES AND TESTS

THERMAL EXPANSION

Thermal expansion of ferrous metals is of particular interest in the design and installation of equipment for high-temperature service and there are included in the appended bibliography references relating to such data for irons and steels. It may be well to point out that the average coefficient for annealed structural carbon and the majority of current commercial structural alloy steels recently tested by Souder(193, 194) is between about 6.5×10^{-6} and 7.5×10^{-6} parts per unit length per 1° F. over the temperature range 75 to 570° F. (25 to 300° C.); in the range from 570 to 1110° F. (300 to 600° C.) it is between 8.0×10^{-6} and 9.3×10^{-6}. Among the principal exceptiona are Invar and some of the related high-nickel steels which have very low expansion coefficients at slightly elevated temperatures but show exceptionally high values in the neighborhood of 750 to 1110° F. (400 to 600° C.). Likewise stainless steel (13 per cent chromium) shows a somewhat lower expansion than the representative values given above. The sample tested by Souder had an average of 6.1×10^{-6} from 75 to 570° F. (25 to 300° C.) and 7.4×10^{-6} in the range from 570 to 1110° F. (300 to 600° C.).

"GROWTH" IN CAST IRONS

Cast irons, as is well known, are subject to permanent changes in volume upon repeated heating and as a result their field of usefulness has been restricted. This effect, which is generally an increase in volume for commercial materials and commonly called "growth," is not only dependent upon temperature and time but also upon composition. According to Rugan and Carpenter(65)[1] white irons shrink and gray irons grow, but in white irons containing appreciably more than 3 per cent carbon there is a tendency to deposit temper carbon upon prolonged heating and the metal will then tend to grow. An alloy of practically constant volume under repeated heating at 1650° F. (900° C.) was found to be a white iron containing about 3 per cent of carbon and only small quantities of other constituents and in particular less than 0.2 or 0.3 per cent of silicon.

---

[1] Attention should be called to the very early studies of the "growth" in cast irons by A. E. Outerbridge, Jr., (51) though the more recent experiments cited better serve the purposes in view for this paper.

Carpenter(65) stated that phosphorus tends to diminish "growth" and that if 0.3 per cent is present, growth is lessened by about 3 per cent. The amount of sulfur present in commercial cast irons is not usually sufficient to have more than a minor influence. Manganese is one of the most important elements to be considered and not only retards the rate of growth but in the majority of cases diminishes the absolute amount. The effect of dissolved gases is negligible in the presence of more than 3 per cent of silicon, but may cause a growth of 1 to 2 per cent in irons containing 1.75 to 3.0 per cent of this element and at least 10 per cent when silicon does not exceed 1 per cent.

As a result of his investigations, Carpenter recommended the use of a "semi-steel" containing about 2.6 per cent of carbon, 0.6 per cent of silicon and 1.6 per cent of manganese for annealing ovens, rolls, fire bars, high-pressure steam valves and turbine casings whose growth, when made from gray irons, is so objectionable a feature. Such metal showed no growth after 150 heatings to high temperatures but on the contrary a slight contraction of about 0.13 per cent.

CHEMICAL STABILITY

In addition to suitable mechanical properties, chemical stability or, as described by Chevenard(170), "chemical inertness" is an important factor in the selection of metals for use at any temperature. It is not considered within the scope of this paper to attempt even a partial review of the large mass of literature relating to corrosion at ordinary or low temperatures but mention should be made of the extensive bibliography relating to this subject recently prepared by Van Patten(207).

While it is well recognized that certain alloys are generally more resistant to chemical changes than others, the greater part of published data on the high temperature stability of ferrous metals is concerned with failures or observations made under specific laboratory or service conditions. Few comparisons of alloy steels at relatively high temperatures have been recorded. Because of this and the fact that many variables are encountered in different types of service only brief reference will be made to typical effects.

Intercrystallin Deterioration.—Failures have not been uncommon in iron or steel parts due to intercrystallin attack resulting in what has been called intercrystallin brittleness. Stress, which may be either internal or external but probably restricted in intensity, nature and distribution, is a necessary condition for such selective attack. However, the active agents producing intercrystallin brittleness may vary widely. Thus in power-plant installations the embrittlement of boiler steels may be the result of reactions with dissolved alkaline substances in the feed water(118). In a case recently brought to the attention of the authors, embrittlement was observed in wrought-iron stirring rods immersed in molten copper and was accompanied by intercrystallin penetration of the copper.

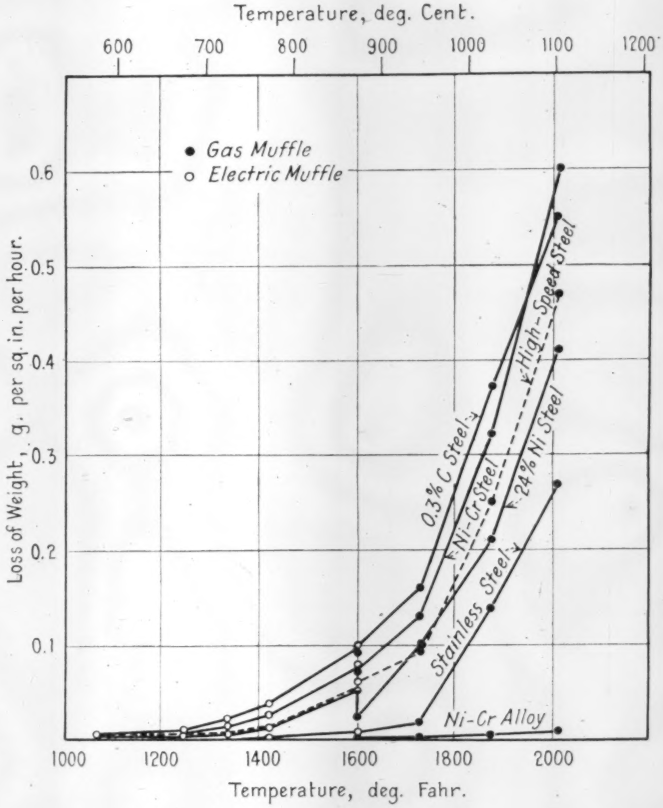

FIG. 17.—Comparison of the Rate of Scaling of Various Steels and a Cast Nickel-Chromium Alloy at Elevated Temperatures [Dickenson (172)].

Composition and treatment of the steels are given in Table II. The nickel-chromium alloy contains 0.54 per cent C; 0.73 per cent Si; 0.10 per cent Mn; 69.9 per cent Ni; 15.5 per cent Cr. Tests carried out in either gas-fired or electric furnaces as indicated.

The intercrystallin cracking of mild steel in caustic soda solutions has been attributed to the weakening of grain boundaries due to hydrogen absorption by the intercrystallin material alleged by one school of metallurgists to be amorphous. Jones(167) has shown that solutions of nitrates also yield a product having a selective action on the intercrystallin material and suggests that this may be nitrogen or an oxide of nitrogen. However, intercrystallin fracture of metals may possibly occur, according to Hanson(167), "as a result solely of the stresses but corrosive agents might act in accelerating them" and likewise cases are cited where material, relatively free from stresses, has developed intercrystallin fracture due to cementite envelopes, etc.

It is not intended to discuss all possible causes of intercrystallin brittleness and fracture but merely to point out (1) that such effects are observed in steels under a variety of conditions in which stress and corrosive agents have been present, (2) that few data are available for comparison of various ferrous alloys and (3) that with increasing demands upon materials for high-temperature service, both with respect to stresses and temperatures, further attention must be given to this important subject.

Oxidation of Steels.—The relative resistance to oxidation of alloy steels in air has recently been studied by Aitchison(123) and Dickenson(172). As the result of extensive tests of carbon, chromium, nickel, nickel-chromium and tungsten steels, the former concluded:

> "That the high-chromium steels present the greatest resistance to scaling at high temperatures of any of the steels. Those of the "stainless" type (13 per cent chromium) give a very high resistance whilst those containing about 7 per cent of chromium give a very fair resistance though not quite so good as that of the stainless steels. In the latter case, however, the scale is more adherent than in the case of the stainless steel type."
>
> "That the nickel-chromium steels (ordinary structural types) scale to a greater extent than do the steels of any of the other types."
>
> "That the tungsten steels scale comparatively little up to temperatures of about 1560° F. (850° C.), but beyond that they are liable to scale very considerably."

Results obtained by Dickenson(172) are partially summarized in Fig. 17 and likewise show the superiority of the stainless steel in comparison with carbon, ordinary nickel-chromium, high-nickel and high-speed steels. However, an iron alloy containing high proportions of nickel and chromium is much superior to stainless steel. Dickenson also pointed out a marked difference in the formation of the scale produced in steels containing nickel and those without appreciable quantities of this element. The former all showed the characteristic "double scale" described by Stead(115) in which the lower layer contains a large proportion of metal.

TREND OF DEVELOPMENT OF "HEAT-RESISTING" ALLOYS

The foregoing sketch of available data, while incomplete, shows clearly that irons and steels have serious limitations for high-temperature service. In the case of cast and malleable irons and semi-steels this is further substantiated by the recommendations of one manufacturer of power plant equipment:[1]

> "Cast iron is recommended for a total temperature of 500° F. (260° C.) when the pressure does not exceed 25 lb. gage and for 100° F. (40° C.) when the gage pressure is not greater than 75 lb. Malleable iron and semi-steels are recommended for temperatures up to 500° F. (260° C.) when the pressure does not exceed 200 lb. gage; at higher temperatures and pressures cast or forged steels are recommended."

As already indicated, the composition and treatment of steels may be varied to meet specific requirements at temperatures above 500° F. (260° C.). However, it is also evident from the described data that all steels "weaken" with considerable rise in temperature. While this weakening may be delayed by additions of relatively large proportions of such elements as chromium, the resulting product retains, in this respect at least, the characteristic properties of the iron which forms the largest part of the alloy, and steels would not generally be expected to stand up under fairly high stress at temperatures exceeding about 1200° F. (650° C.). Thus for service at higher temperatures it would appear necessary to seek alloys in which the iron plays a secondary rôle instead of forming the largest part of the product.

In this connection it will be of interest to cite briefly the result of experiences encountered with the direct synthetic ammonia process as summarized by Vanick.[2]

> "The fixation of nitrogen by the synthetic ammonia processes requires metal tubes and containers capable of conveying or holding corrosive gas at high temperatures and high pressures. A gas-proof, forgeable, machineable corrosive-resisting and heat-resisting material is required. The Fixed Nitrogen Research Laboratory of the Department of Agriculture has completed an extensive investigation of plain carbon and alloy steels that might be applied to this service.
>
> "Of the commercially obtainable alloy steels in the 0.30 to 0.40-per-cent carbon range, those containing chromium or tungsten or both elements showed a superior resistance to deterioration over other alloy steels. A series of chromium-vanadium steels containing up to 21 per cent chromium showed an improvement in resistance to deterioration which increased with the percentage of chromium in the alloy. For the purposes which the laboratory had in view, a $2\frac{1}{2}$-per-cent chromium steel was selected as suitable for the type of service demanded of a metal in the direct synthetic ammonia process. These results apply to the special conditions of test representing 100 atmospheres pressure of synthetic mixtures at 930° F. (500° C.). No significant improvement in tensile properties at elevated temperatures was obtained with these steels.

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[1] Data obtained from correspondence.

[2] This summary was prepared at request of the authors by Mr. J. S. Vanick, formerly of the Fixed Nitrogen Research Laboratory, U. S. Department of Agriculture.

"Long before this position in the development of materials had insured temporary security, new achievements in the same field of chemistry were requiring better materials to hold the same gases at super-pressures and perhaps super-temperatures, with respect to earlier processes. Pressures which can be held at ordinary temperatures exert stresses at the operating, elevated temperatures that would correspond to or exceed the limit of elasticity for practically all steels and ferrous alloys. So important has high-temperature strength become for this service that the property of resistance to corrosion which had thus far been associated with it, may be subordinated; partly because most of the elements which possess the property of strength or coherence at elevated temperatures also possess, in this case, a superior resistance to corrosion or deterioration."

"New investigations are leading into alloys of the inelastic type; alloys which possess a yield point at ordinary temperatures that closely approaches the ultimate strength. At elevated temperatures some plasticity would be expected which would not necessarily imply elasticity. At present these alloys are expensive, unmachineable, must be cast to shape with the difficulty that attends viscous fusions, and in the present state of development improve the high-temperature strength very slightly. For service as tubes or containers for gas under pressure, such defects as porosity and segregation delay their acceptance."

"Work on these important alloys will clear many of the obstructions now encountered in their preparation and lead to new developments in the strength-at-high-temperature field."

Some of the features pointed out by Vanick are in substantial agreement with experiences encountered in France in the production of ammonia by the Claude process. The development of materials in this case is reported by LeChatelier[1] as follows:

"Mr. Claude had begun his experiments with a mild steel tube under a pressure of a thousand atmospheres, water-cooled and heated internally by a helix through which was passed electric current. He [Professor LeChatelier] had made the suggestion that as iron possessed considerable tensile strength at 750° F. (400° C.) it would be sufficient for the purpose to plunge the tube into a bath of lead and thus reduce considerably the consumption of electric energy. From the first the experiment succeeded, and Mr. Claude was able to obtain from the outlet of his tube liquid ammonia, the problem being thus apparently solved. Unfortunately, after a run of six hours the plant exploded. . . . Experiments made under the same pressure of a thousand atmospheres and at a temperature of 1110° F. (600° C.) on iron wires showed that the nitrogen had no action but that the hydrogen caused rapid alteration in the metal similar to that observed in the case of the tube referred to above. It was necessary, therefore, to find a metal which would resist the action of hydrogen. . . . Mr. Chevenard suggested in the first instance a steel having a composition similar to that of high-speed steel. . . . That steel underwent without difficulty a pressure of a thousand atmospheres at 1110° F. (600° C.). It was no longer necessary to resort to internal heating: the heat evolved by the reaction was sufficient to a great extent to maintain a temperature of 1110° F. (600° C.) at the point where the external cooling was not too great. Once again it was assumed that a final solution of the problem had been found but after a hundred hours of working the tube again exploded."

---

[1] Discussion of report by Dickenson (**172**).

"Mr. Chevenard then suggested the use of another 'steel' having the following composition: Nickel, 60 per cent; iron, 25 per cent; chromium, 12 per cent; manganese, 2 per cent; carbon, 0.5 per cent. The tubes from that metal yielded excellent service and tubes of larger dimensions were therefore ordered capable of being employed in normal manufacture. It was found impossible to forge the large ingots and necessary to employ the metal as cast. The tubes behaved, nevertheless, very well in service and some of them had already been in use for five thousand hours."

TABLE IV.—SOME "HEAT-RESISTANT" ALLOYS NOW IN USE OR PROPOSED FOR HIGH TEMPERATURE SERVICE OF VARIOUS TYPES.[1]

(Approximate Type Compositions Unless Otherwise Specified)

Manufacturer or Name	Chemical Composition, per cent									Remarks
	C	Mn	Ni	Cr	W	Co	Si	Fe	Cu	
GROUP I. STEELS										
I (*a*) Stainless iron..	Under 0.12	...	....	11 to 14	....	..	...	....	..	
(*b*) Stainless steel..	0.2 to 0.4	...	....	11 to 14	....	..	...	....	..	
(*c*) Manufacturer A	Under 0.8	...	....	18 to 20	....	..	...	....	..	
(*d*) " B	0.5	...	....	25	....	..	0.4	....	..	
(*e*) " C	0.3	...	....	28 to 30	....	..	...	....	..	
(*f*) " D	0.30	0.30	....	19.0	3.0	..	2.75	....	..	P, 0.02 S, 0.02 Actual analysis
(*g*) " E	0.3	...	....	20	....	..	...	....	1	
(*h*) " F	0.4	0.23	15.3	16.0	....	..	3.22	....	..	Actual analysis
(*j*) " G	1.75 to 2.00	...	5	20	....	..	...	....	..	
(*k*) " H	0.4	...	21	7.5	....	..	1.5	....	..	
GROUP II. NICKEL-CHROMIUM-IRON-BASE ALLOYS										
II (*a*) French patent 469, 929......	0.3 to 1.0	1 to 5	50 to 80	8 to 25	0.5 to 8.0	..	...	......	..	Tungsten may be partially replaced by Molybdenum
(*b*) French Alloy "ATG"......	....	...	60	10	4	..	...	Remainder	..	See text and Fig. 18
(*c*) French alloy....	0.5	2	60	12	....	..	...	25	..	See text
(*d*) Manufacturer J.	....	...	62	11	....	..	...	25	..	
(*e*) Manufacturer J, K, L, M, N...	0.5	2	68	17	....	..	1	10.75	..	Mo, 0.75
(*f*) Manufacturer G	0.2 to 1.25	...	35	15	....	..	...	47	..	
GROUP III. ALLOYS FREE FROM OR LOW IN IRON										
III (*a*) Manufacturer J	....	...	80	20	....	..	...	......	..	
(*b*) " J	....	3	94	....	....	..	1	......	..	Al, 2
(*c*) " O	.....	...	80	11	....	..	...	6	..	
(*d*) " J	0.2	1.5	83.5	13.5	....	..	0.3	0.5	..	
(*e*) German alloy (Tammann)..	....	...	....	25	....	75	...	......	..	See text
(*f*) German alloy (Tammann)..	....	...	....	30	....	70	...	......	..	See text
(*g*) Aluminum-nickel	Under 0.15	0.3	97	....	....	..	0.3	0.5	..	Al, 1.8
(*h*) Manganese-nickel	0.2	3	95+	....	....	..	...	1	..	
(*j*) "A" nickel.....	0.15	0.2	99	....	....	..	...	Remainder	..	

---

[1] Copper-nickel and other non-ferrous alloys especially adapted for service at steam temperatures are not considered.

Quite a number of "heat-resisting" alloys are now produced commercially in this country and others have been shown to have desirable properties at very high temperatures. Many of these cannot be called steels or even ferrous alloys and in some cases are practically free from iron but they will be briefly considered to show the present trend in development of metals well adapted for various types of high-temperature service under which ordinary steels fail to meet at least some requirements.

In Table IV, in which is given a partial but representative list of such metals, an arbitrary division has been made depending upon the iron content. The first group comprises steels with relatively large proportions of special elements but containing over 50 per cent of iron; the third group consists of alloys practically free from this element or with proportions up to 4 or 8 per cent in the nature of an impurity; the second is an intermediate group with from about 10 to 50 per cent of iron. Commercial non-ferrous alloys for service at steam temperatures are not considered.

Except in two cases the steels of Group I, Table IV, are low in carbon and are based upon chromium additions of from 11 to 30 per cent. However, they may also contain varying amounts of one or more of the elements, nickel, tungsten, silicon and copper and such additions may be expected to modify the properties obtained. Steels similar to No. I (*h*) have exceptionally good resistance to oxidation at high temperatures and have been discussed by Johnson(**108**).

The alloys in Group II are primarily nickel-chromium-iron alloys with or without additions of tungsten, manganese, silicon and molybdenum and in the majority of cases are quite close to or within the limits given under No. II(*a*), Table IV. They have been used to advantage for a variety of purposes including furnace parts, containers employed in the heat treatment of metals, etc. One of these, as has already been indicated, has been used in France for tubes employed in production of ammonia by the Claude process. The mechanical properties of two of the alloys in this group are shown in Fig. 18 in comparison with heat-treated stainless steel and a chromium-molybdenum structural steel.

In addition to alloys of nickel with chromium, manganese, aluminum and silicon, Group No. III contains two cobalt-chromium combinations, mentioned by Tammann,[1] which are reported to have very desirable mechanical properties in the neighborhood of 1300 to 1500° F. (705 to 815° C.). Alloy No. III(*e*), Table IV, showed an elastic limit of about 40,000 lb. per sq. in. at 1470° F. (800° C.) and No. III(*f*) about 65,000 lb. per sq. in. at 1330° F. (720° C.). Nickel, or alloys containing very large proportions of this element, as shown in Group III, have excellent resistance to oxidation at temperatures up to 1830° F. (1000° C.) in atmospheres relatively free from sulfur but not high strength when considering sustained loads. Some, as in the case of Nos. III(*a*), (*b*) and (*c*) have special electrical properties which make them particularly useful.

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[1] Refer to discussion of Dickenson's report (**172**).

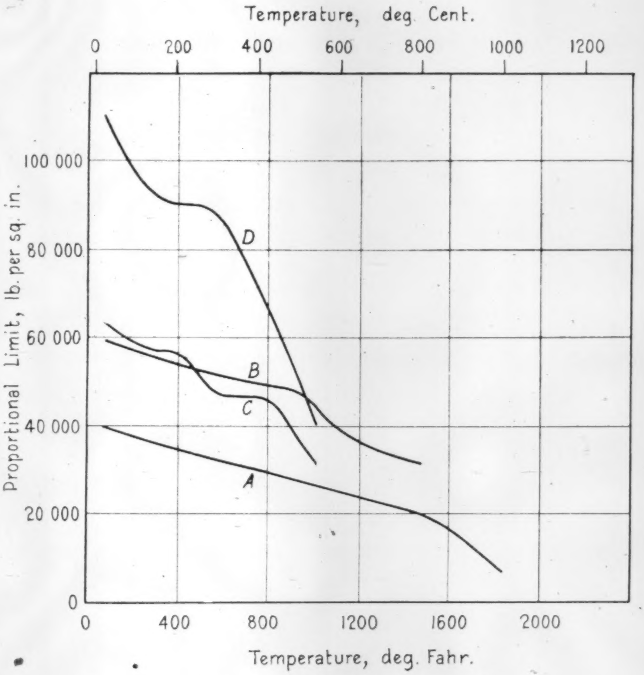

FIG. 18.—Effect of Temperature on the Proportional Limit of Chromium-Molybdenum and Stainless Steels and Two Nickel-Chromium-Iron Alloys (Collected from Various Sources).

A—Nickel-chromium-iron alloy containing approximately 0.8 per cent C; 35 per cent Ni; 15 per cent Cr. Tested as cast. Data obtained by the authors.

B—Nickel-chromium-iron-tungsten alloy containing about 60 per cent Ni; 10 per cent Cr; 4 per cent W; 25 per cent Fe [Guillet (**100**)].

C—Steel containing 0.27 per cent C; 0.99 per cent Cr; 0.41 per cent Mo. Oil quenched from 1550° F. (845° C.); tempered at 1110° F. (600° C.). [French and Tucker (**196**)].

D—Stainless steel containing 0.31 per cent C; 12.75 per cent Cr. Oil quenched from 1750° F. (955° C.); tempered at 1250° F. (675° C.) [French (**180**)].

Note the rapid decrease in the proportional limit of the steels above 800° F. (425° C.) as compared with the two nickel-chromium-iron alloys.

In conclusion, mention should be made of the possible developments in the use of coated metals for high-temperature service. Aluminum (calorizing) and chromium (chromizing) coatings appear to offer promising developments in this field.

AVAILABLE DATA ON THE PROPERTIES OF NON-FERROUS METALS AND ALLOYS AT VARIOUS TEMPERATURES

Clair Upthegrove[1] and A. E. White[2]

Introduction

The physical properties of the non-ferrous metals at elevated temperatures have attracted the attention of relatively few investigators. While considerable study has been given to the properties of iron and steel at elevated temperatures, non-ferrous materials have received but little attention until very recently. Moreover, the present attention given is not in keeping with their importance.

One of the earliest investigations of non-ferrous alloys at elevated temperatures was carried out in 1877 by the British Admiralty at the Portsmouth Dockyard. The test bars were first heated in an oil bath and then transferred as quickly as possible to the testing machine and broken. Even this very crude arrangement gave remarkably accurate results. In 1890, Martens reported, in connection with a series of tests on iron and steel at elevated temperatures, the results of some tests on copper. This seemingly represents the beginning of a series of tests by Rudeloff, Stribeck, Unwin, Charpy, Bach and Le Chatelier. Their investigations of non-ferrous metals were confined mainly to copper, although Rudeloff made a rather extensive investigation of high-manganese bronzes and Delta metal. The results of these were given quite largely in Rudeloff's report on "The Influence of Increased Temperatures on the Mechanical Qualities of Metals."

In more recent years the properties of non-ferrous metals at elevated temperatures have been contributed to very largely by Huntington, Bengough, Hanson, Edwards, Rosenhain, Lea, Doernickel and Trockels in Europe, and by Bregowsky and Spring, Jeffries and Sykes, and very recently by Malcolm in this country. Of this work, both in this country and abroad, a considerable proportion has had as its primary purpose the determination of certain scientific facts rather than physical properties, although the latter have not been ignored. As a result many of the tests have been carried out under very widely varying conditions as to the nature of the material, that is, composition, degree of working or of annealing, size of specimens, method of heating, temperature measurement, nature of atmosphere in which the tests were made, and method and rate of loading. The work of Lea and of the National Physical Laboratory of England on aluminum alloys stands forth as that of well organized and systematic tests, the primary purpose of which is the determination of the physical properties. Similarly, in this country, the work of Bregowsky and Spring, and the more recent investigations of Malcolm, represents work which has had as its primary purpose the determination of the physical properties.

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The purpose of this paper is not to present all of the work which has been done on the physical properties of non-ferrous metals at elevated temperatures, but to present as far as possible typical properties for the various metals which have been investigated. In many cases alloys have been investigated by only one individual, or investigators have used materials so widely different in composition as to represent in reality two entirely different alloys. In view of this condition and the limited development of the art of the testing of non-ferrous alloys at elevated temperatures, it has seemed unwise to include values from any other than the original sources. In one case, where the original author has drawn his curves to emphasize certain inflections or critical points the values have been replotted and the curves drawn as average curves. (Figs. 2, 13 and 14.)

No attempt has been made to consider the methods of testing, that being considered beyond the scope of this paper.

COPPER

Copper, though somewhat limited in its field of application at high temperatures, has apparently invited the attention of a number of investigators. Rudeloff (1893–1898), Unwin (1899), Le Chatelier (1901), and Stribeck (1903) made tests on copper at elevated temperatures. The results of these tests were presented by Rudeloff(**27,64**) in his official report, "Influence of Increased Temperatures on the Mechanical Qualities of Metals," made to the International Association for Testing Materials in 1909. The results presented, while extending over narrower ranges of temperature than used by later investigators, showed in addition to the actual temperature effects, the influence of composition, of cold working and of the rate of loading. Rudeloff found the tensile strength of cold-worked copper superior to that of annealed copper at the lower temperatures. At higher temperatures this difference disappeared. Tin in copper was

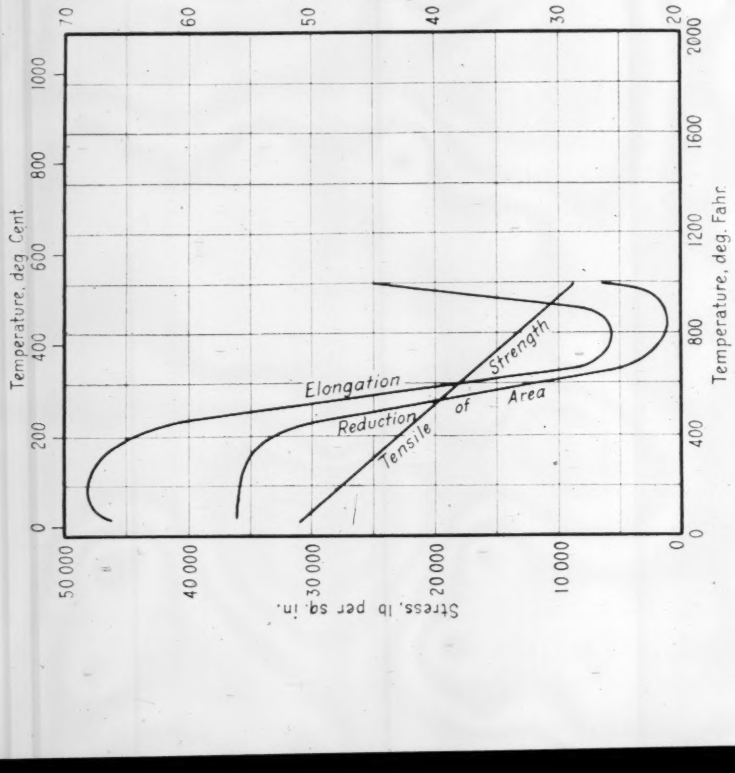

FIG. 1.—Effect of Temperature on Tensile Properties of Electrolytic Copper, According to Huntington (**85**).

Annealed at 1112° F. (600° C.).

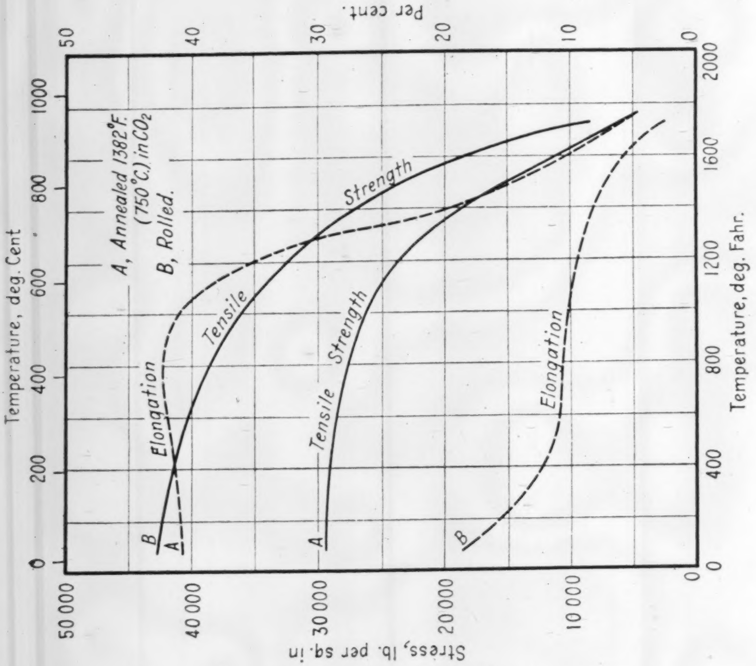

FIG. 2.—Effect of Temperature on Tensile Properties of Electrolytic Copper, According to Bengough and Hanson (**96**).

Broken in Carbon Dioxide.

found not only to aid in retention of the tensile strength but to increase in a very marked manner the tensile strength at the higher temperatures. Stribeck(**48**) found lower tensile values but used a slower rate of loading. These tendencies have all been confirmed by the later investigators, though the degree to which these factors influence properties or the temperatures at which the effects are most marked are not always in agreement with the earlier results.

In the period following the presentation of Rudeloff's report and up to the present time, investigations of copper at elevated temperatures have been made by Huntington, Bengough and Hanson, Jeffries, Hughes, Doernickel and Trockels, and others. While the methods of testing used by both Huntington and Bengough have been subjected to considerable criticism, particularly the method of heating used by Huntington and the method of loading employed by Bengough, their results are of decided interest.

The tensile properties of electrolytic copper as determined by Huntington(**85**)[1] and by Bengough and Hanson(**96**) are shown in Figs. 1 and 2. In Fig. 3 Bengough's(**82**) tensile properties of a cold-rolled copper carrying 0.05 per cent arsenic are shown. Annealed electrolytic copper, according to Bengough and Hanson, shows when tested in an atmosphere of carbon dioxide quite different properties than when tested in air. In air, tensile strength falls off rapidly with increasing temperatures, while the elongation decreases somewhat slowly up to 400 to 500° F. (205 to 260° C.) and then very rapidly to a minimum. Tested in an atmosphere of carbon dioxide, both tensile strength and elongation are retained practically undiminished up to temperatures of 950 to 1050° F. (510 to 565° C.). Above these temperatures both tensile strength and elongation decrease rapidly. In the rolled condition, the electrolytic copper shows a slightly greater decrease in strength at low temperatures. The elongation decreases rapidly up to temperatures of 400 to 500° F. (205 to 260° C.), remains unchanged up to 1100 to 1200° F. (600 to 650° C.), followed by a rapid decrease. It will be noted that neither the rolled nor the annealed electrolytic copper shows a reversal in elongation if tested in carbon dioxide. Bengough, however, did obtain a reversal in elongation for cold-rolled copper tested in air (Fig. 3). In his opinion, this marked difference in behavior of the tensile properties of copper at the higher temperatures was due to the influence of arsenic in the copper and the presence of the oxidizing atmosphere. The decrease in elongation between 400 and 500° F. (205 to 260° C.) observed by Huntington and by earlier investigators, it was suggested, might be due to the influence of the annealing.

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[1] The boldface numbers in parentheses refer to the papers of the Bibliography appended hereto, page 128.

Jeffries' work(127) on tensile properties of copper wire at temperatures above and below atmospheric temperature are not entirely in agreement with those of Bengough and Hanson. Jeffries used electrolytic copper and an atmosphere of argon for all tests above 400° F. (205° C.). With annealed copper wire a decrease in elongation was observed at 400 to 500° F. (205 to 260° C.) by Jeffries but no indication of a reversal at 800° F. (425° C.), the elongation decreasing continuously. With cold-drawn electrolytic copper, Jeffries shows a decrease in elongation followed by a very rapid increase at a temperature lying between 800 and 900° F. (425 and 480° C.), a change similar to that observed by Huntington for annealed copper.

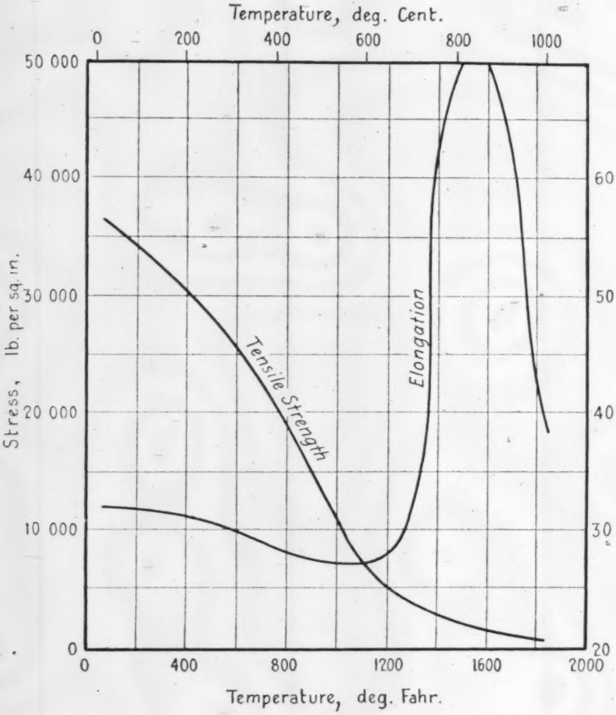

FIG. 3.—Effect of Temperature on Tensile Properties of Copper, According to Bengough(82).

Chemical Composition, per cent: Cu, 99.84; As, 0.05; Mn, 0.08; Fe, trace; S, 0.005.

Although Jeffries' results were obtained on small wires and a faster rate of loading was used by him than by Bengough and Hanson, the regularity with which the reversal in elongation in the neighborhood of 800° F. (425° C.) occurred on the cold-rolled copper, leaves the question of the behavior of cold-rolled electrolytic copper when tested as above somewhat in doubt. Either the results obtained by Bengough and Hanson and by Jeffries are open to question or factors other than the presence of oxygen or arsenic contribute to this difference.

The above variations in the tensile properties of copper at elevated temperatures have been pointed out primarily to show how very readily the tensile properties, particularly the elongation, are influenced by the presence of factors other than the temperature alone. The presence of impurities, oxidizing or non-oxidizing conditions, cold working, the degree of annealing, the rate of loading, method of testing—all may have a very decided influence on the tensile properties, though usually to a greater degree on the elongation.

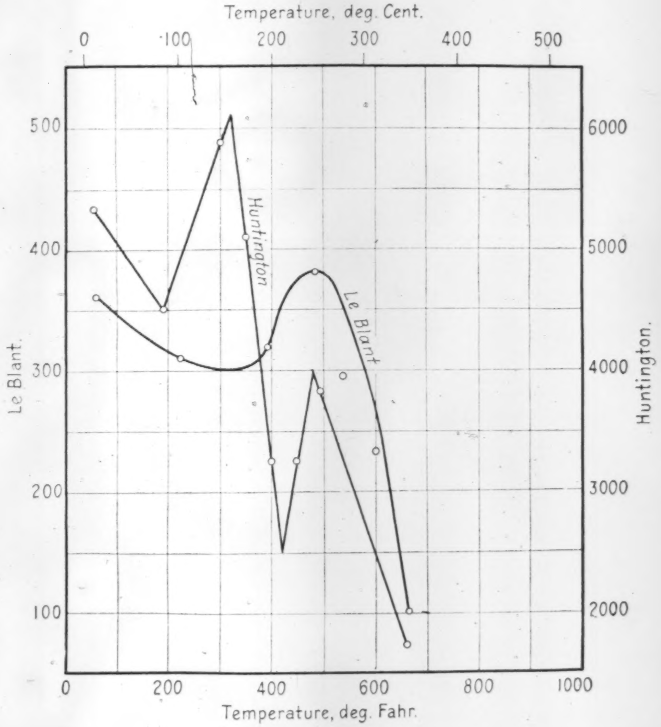

FIG. 4.—Effect of Temperature on Resistance to Alternate Bending of Copper, According to Huntington(107) and Le Blant(34).

For average conditions the changes in tensile properties of copper at elevated temperatures will conform in general to the changes noted by Huntington (Fig. 1). Rolled copper will show a tensile strength superior to that of annealed copper at the lower temperatures. Both tensile strength and elongation differences for rolled and annealed copper will disappear at higher temperatures, or even at lower temperatures if held sufficiently long for an annealing effect to occur.

Additional tests on copper at elevated temperatures which may properly be mentioned are hardness tests by Kürth(62) and Ludwik(112), low-temperature tests by Jeffries(127), alternate stress or bending tests by Huntington(107), modulus determinations by Iokibe and Sakai(154) and crushing tests by Doernickel and Trockels(149).

Kürth(62) has shown the hardness of copper to decrease gradually with increasing temperatures. Confirmatory results have been obtained by Ludwik(112), who also investigated hardness of lead, zinc, aluminum, tin, antimony, cadmium, and bismuth. According to Ludwik the influence of the time of loading becomes very important at higher temperatures, a 15-second and a 300-second loading resulting in a 40 to 50-per-cent difference in hardness values at 900 to 1000° F. (480 to 540° C.). Huntington (Fig. 4) found the resistance to bending stresses decreases very little at temperatures up to 350 to 400° F. (175 to 205° C.). Le Blant(25) in earlier investigations found little decrease up to 500° F. (260° C.). Jeffries in his tests of metals below atmospheric temperatures obtained a tensile strength of 80,000 lb. per sq. in. and 6 per cent elongation for cold-drawn copper at $-301°$ F. ($-185°$ C.). Tensile strength and elongation of both cold-drawn and annealed copper are increased at temperatures below atmospheric. Doernickel and Trockels (Figs. 19 and 20) show the crushing strength to decrease gradually with temperature. Modulus of elasticity, according to Iokibe and Sakai, decreases according to a parabolic law.

COPPER-TIN BRONZES

The influence of temperature upon the properties of copper-tin bronzes (Fig. 5), according to Bregowsky and Spring(4), becomes most marked between 400 and 600° F. (205 and 315° C.), all of the properties except the elastic limit decreasing very rapidly within that range of temperature. At temperatures below 300 to 350° F. (150 to 175° C.) no appreciable difference in tensile strength is found for the bronzes carrying 12 per cent of tin. At all higher temperatures the 12-per-cent bronze is superior in strength to the bronze of a lower tin content. The influence of the additional tin is also shown in the effect on elongation and reduction of area at temperatures above 750° F. (400° C.). Variations in properties at elevated temperatures seemingly are dependent upon the presence of the delta constituent, the final

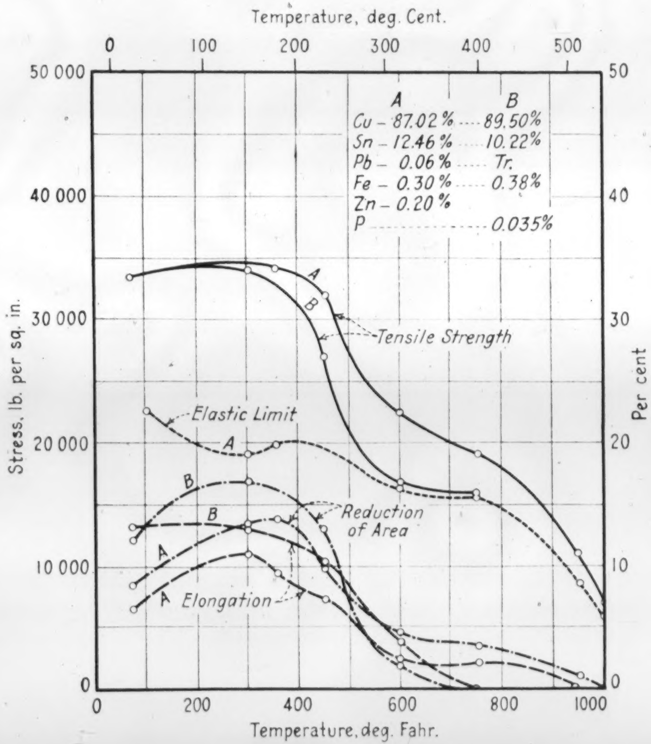

FIG. 5.—Effect of Temperature on Tensile Properties of Copper-Tin Bronze, According to Bregowsky and Spring(83).

Chemical Composition as Indicated.

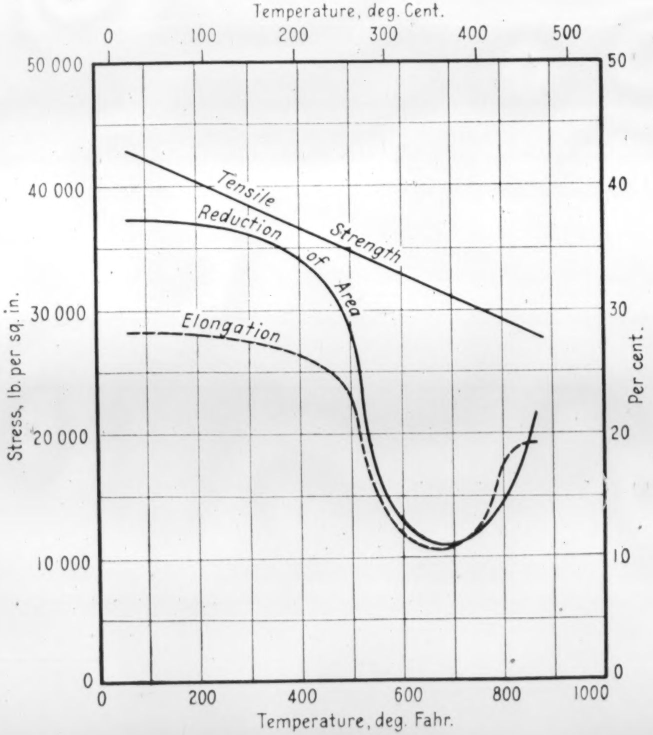

FIG. 6.—Effect of Temperature on Tensile Properties of Copper Tin Bronze, According to Huntington(85).

Chemical Composition, per cent: Cu, 97.673; Sn, 2.408; Pb, 0.024.

decrease in elongation and tensile strength coming at the temperatures corresponding to the absorption of this constituent. In view of the much higher elastic limit values obtained by Bregowsky and Spring on gun-metal bronzes than have been obtained by other investigators, the elastic limit values given in Fig. 5 may be higher than further investigation will prove to be the case.

Low-tin bronze (Fig. 6), according to Huntington(85), shows a gradual decrease in strength with increasing temperature. Elongation and reduction of area decrease rapidly at 500° F. (260° C.), reaching a minimum at 700° F. (370° C.). The results obtained by Huntington are very similar to the results obtained in 1893 by Rudeloff(20,64) with copper carrying 1.86 per cent tin. This copper-tin alloy shows a tensile strength superior to that of copper at all temperatures up to 900° F. (480° C.).

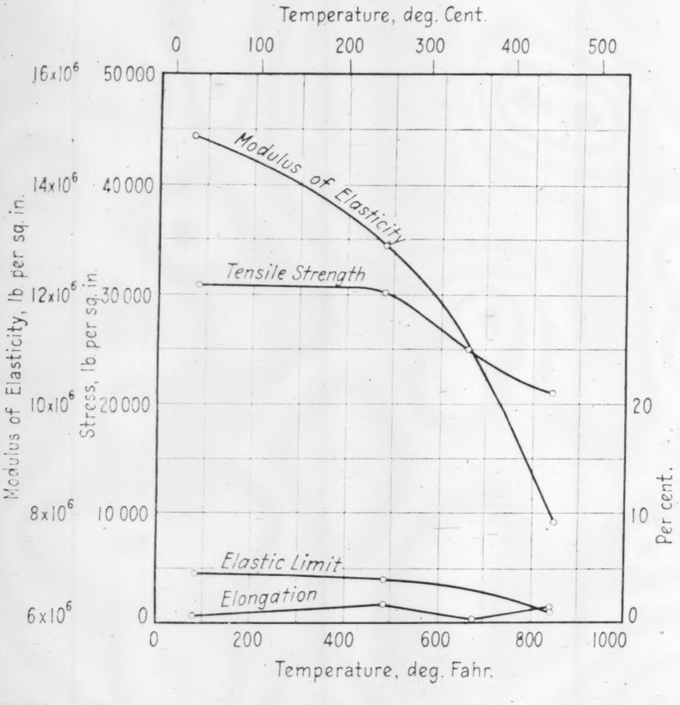

FIG. 7.—Effect of Temperature on Tensile Properties of Phosphor Bronze, According to Lea(142).

Chemical Composition, per cent: Cu, 85.38; Sn, 12.55; Zn, 1.01; P, 0.24; Fe, 0.02; Pb, 0.61; Ni, 0.11.

PHOSPHOR BRONZE

Phosphor bronze (Fig. 7) retains its tensile strength undiminished up to temperatures of 450 to 500° F. (230 to 260° C.). Above 500° F. (260° C.) the strength and elastic properties decrease rapidly. According to Lea(142), the elastic limit becomes zero and the tensile strength decreases to less than 5000 lb. per sq. in. above 900° F. (480° C.).

GUN METAL

Tensile properties of gun metal, according to Lea(141,142) (Fig. 8), undergo no appreciable change up to 450 to 500° F. (230 to 260° C.). Above 500° F. (260° C.) the tensile strength and elongation decrease very rapidly. The elastic limit decreases more slowly but reaches a value of less than 4000 lb. per sq. in. at 850° F. (450° C.). Hardness decreases slowly with increase in temperature. The tensile properties of gun metal show a slight superiority over phosphor bronze for temperatures up to 450 to 500° F. (230 to 260° C.).

Bregowsky and Spring(83), in an earlier investigation, obtained very similar results for U. S. Navy Gun Bronze, though slightly lower values are given for tensile strength and for elongation than are obtained by Lea. Values for permanent set differ very widely from those obtained by Lea. The initial value at normal temperatures is given as 25,100 lb. per sq. in. as opposed to 7150 lb. per sq. in. by Lea. At 750° F. (400° C.) a value of 17,500 lb. per sq. in. is given as opposed to less than 5000 lb. per sq. in. by Lea. This difference indicates the necessity for a careful check.

Influence of 0.5 per cent of lead has been considered by Dewrance(98). Gun metal without lead (Fig. 9) undergoes no decrease in its tensile properties up to 350° F. (175° C.). Above that temperature tensile strength and elongation decrease rapidly up to 400° F. (205° C.), remaining constant up to 600° F. (315° C.), and again decreasing. With 0.5 per cent of lead present, the tensile strength and elongation remain undiminished up to a temperature of 550° F. (290° C.). Above that temperature tensile strength and elongation decrease rapidly. The retention of the tensile strength at higher temperatures with the second alloy is attributed by Dewrance to the presence of the lead. As neither Bregowsky and Spring nor Lea reported tests at 550° F. (290° C.), their results cannot be used directly to confirm or deny the results obtained by Dewrance, although Lea used an alloy with 0.12 per cent of lead and Bregowsky and Spring an alloy with 0.39 per cent of lead. However, the fact that Lea, using an alloy with

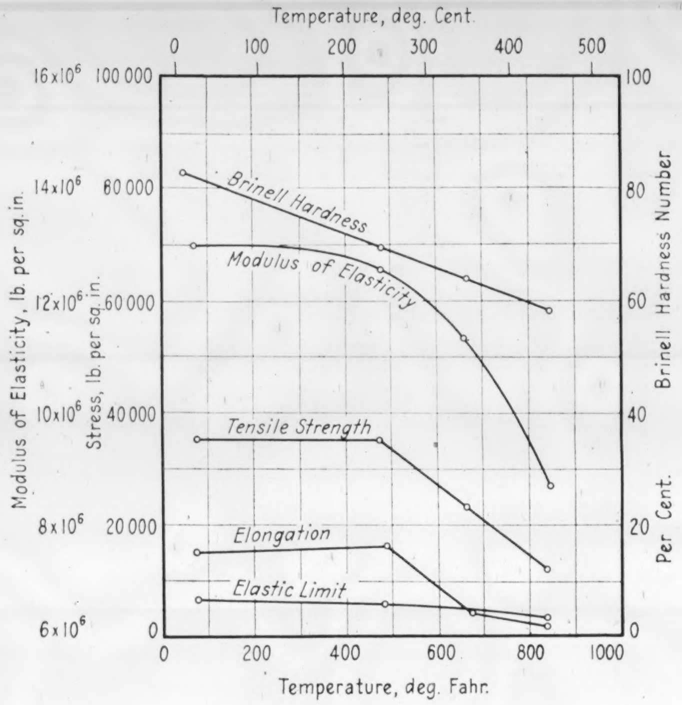

FIG. 8.—Effect of Temperature on Tensile Properties and Brinell Hardness of Gun Metal, According to Lea (**141,142**).

Chemical Composition, per cent: Cu, 86.52; Sn, 10.2; Zn, 3.29; Pb, 0.12.

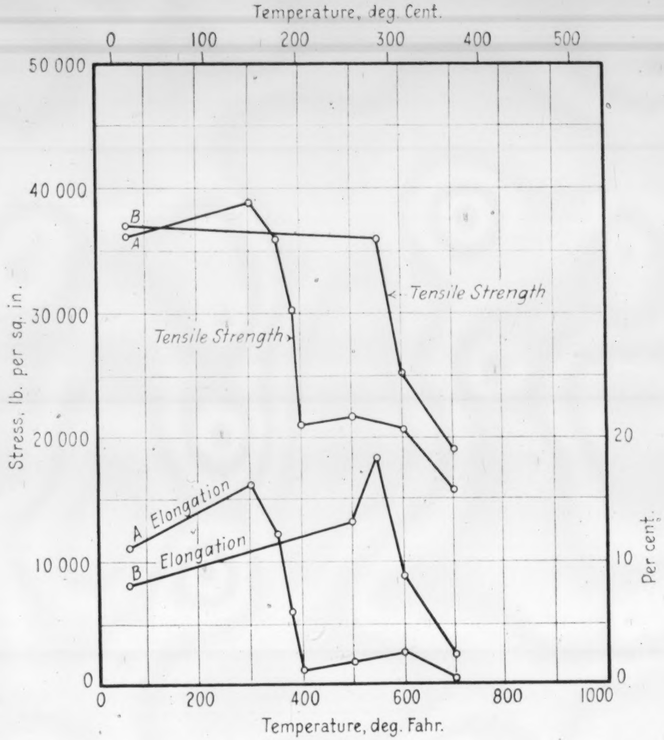

FIG. 9.—Effect of Temperature on Tensile Properties of Gun Metal, According to Dewrance (**98**).

Chemical Composition, per cent: A. Cu, 88; Sn, 10; Zn, 2. B. Cu, 87.5; Sn, 10; Zn, 2; Pb, 0.5.

comparatively low lead content (0.12 per cent), shows the tensile strength unchanged up to a temperature of 482° F. (250° C.) leaves the suggested superiority of the 0.5-per-cent-lead bronze somewhat in doubt. Dewrance gives no analysis of the metal actually tested, but it should be pointed out that his gun metal alloy without lead was made from copper with a purity of 99.55 per cent and carrying 0.08 per cent lead. The sharp increases in elongation noted by Dewrance were not observed by either Lea or Bregowsky and Spring.

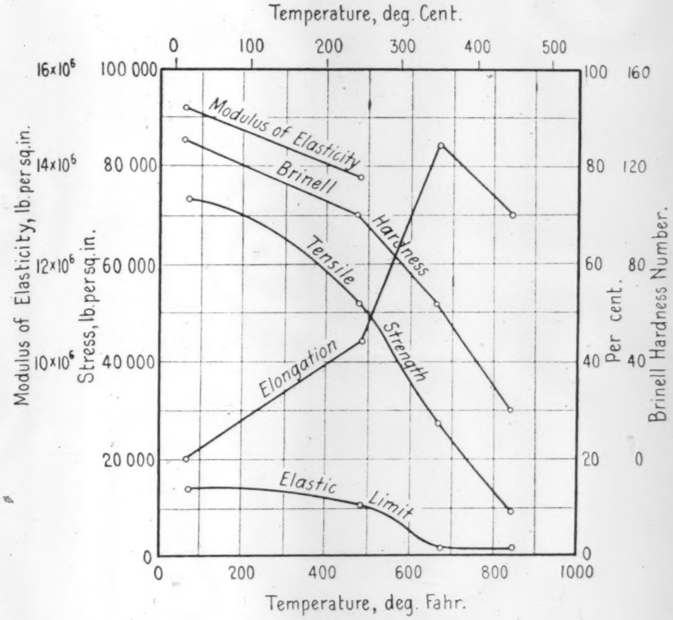

FIG. 10.—Effect of Temperature on Tensile Properties and Brinell Hardness of Cast Manganese Bronze, According to Lea (141,142).

Chemical Composition, per cent: Cu, 58.61; Zn, 36.9; Sn, 0.08; Mn, 1.88; Al, 1.01; Fe, 1.46; Pb, 0.06.

MANGANESE BRONZE

The tensile properties of cast and drawn manganese bronze (Figs. 10 and 11) change rapidly with increasing temperatures. Tensile strength decreases to 60 to 70 per cent of its original value at 500° F. (260° C.). Above that temperature the rate of decrease is more rapid. Elongation of both cast and drawn manganese bronze increases with increasing temperatures, reaching a maximum at 650 to 700° F. (345 to 370° C.), according to Lea (141,142). Brinell hardness changes with tensile strength. Elastic limit decreases slightly up to 500° F. (260° C.), then falls rapidly for cast metal. The elastic limit of drawn metal shows a continuous decrease.

Earlier results of Bregowsky and Spring(83) are in agreement with those of Lea as to tensile strength changes and elongation except for the maximum noted by Bregowsky and Spring at 500° F. (260° C.) and Lea at 650 to 700° F. (345 to 370° C.). As regards elastic limit the shape of the curve is the same for both, no appreciable drop occurring below 450° F. (230° C.). Original values, however, are decidedly different, a difference which undoubtedly reverts to the method of determining elastic limit. In either case the elastic properties of manganese bronze practically disappear between 700 and 800° F. (370 to 425° C.).

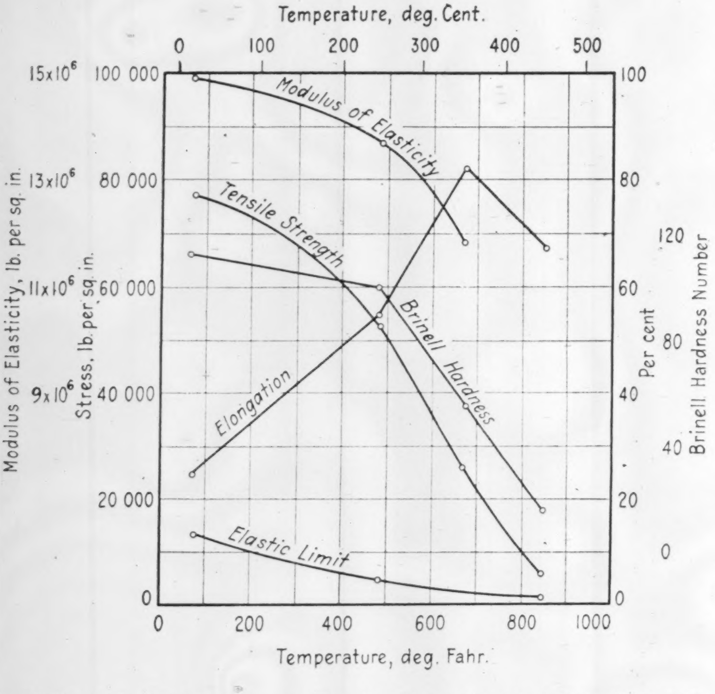

FIG. 11.—Effect of Temperature on Tensile Properties and Brinell Hardness of Drawn Manganese Bronze, According to Lea(141,142).

Chemical Composition, per cent: Cu, 56.91; Zn, 40.28; Sn, 0.75; Mn, 0.19; Fe, 0.82; Pb, 0.66; Al, 0.18; Ni, 0.21.

ALUMINUM BRONZE

Early tests by Rosenhain(57) on rolled aluminum bronze showed the superiority at all temperatures up to 800 to 900° F. (425 to 480° C.)

of the 10-per-cent aluminum bronze over the 5-per-cent bronze. Elongation of the 10-per-cent or two-constituent bronze increases up to 900° F. (480° C.), while the 5-per-cent bronze shows a continuous decrease in elongation. The influence of increasing the percentages of manganese was also tried by Rosenhain but this did not result in material improvement in the properties of the bronze.

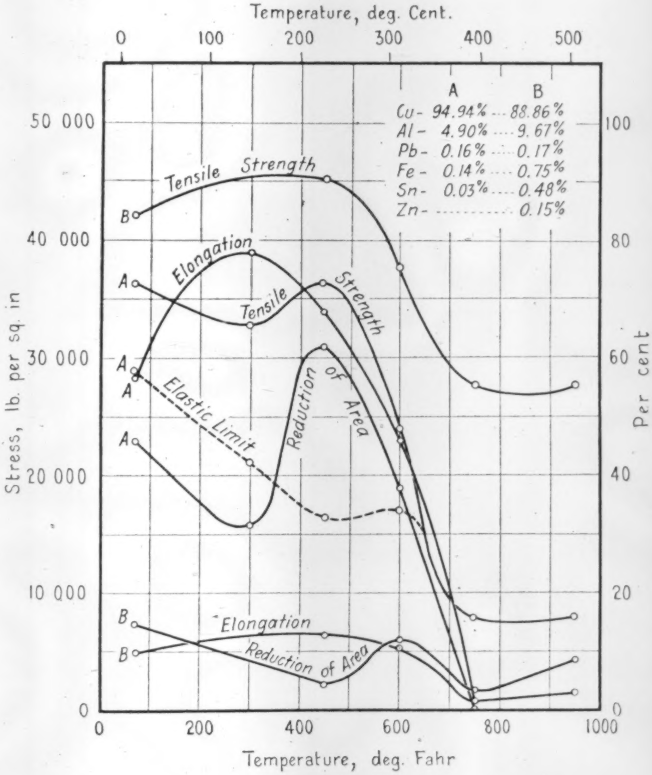

FIG. 12.—Effect of Temperature on Tensile Properties of Aluminum Bronze, According to Bregowsky and Spring(83).

Chemical Composition as Indicated.

Bregowsky and Spring(83) (Fig. 12) found the cast 10-per-cent aluminum bronze superior in tensile strength at all temperatures to the 5-per-cent bronze. No appreciable decrease in strength occurs in the 10-per-cent bronze below 600° F. (315° C.). Above that temperature and up to 900° F. (480° C.), the strength remains very nearly equal to the initial strength of the 5-per-cent bronze.

Edwards and Herbert(151) have also carried out dynamic tests, referred to under brasses, on copper-aluminum alloys.

BRASSES

Tensile properties of brasses at elevated temperatures have been investigated by Bengough and Hanson(96), Huntington(85) and Lea(141,142). Edwards and Herbert(151) have investigated the plasticity of brasses by means of dynamic rather than tension tests, while Doernickel and Trockels(149) have investigated the compressibility.

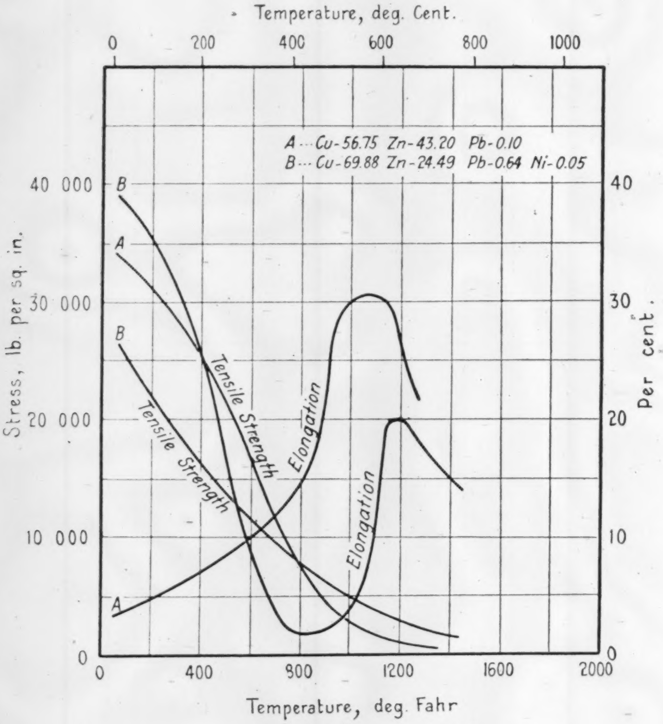

FIG. 13.—Effect of Temperature on Tensile Properties of Cast Brass, According to Bengough(82).
Chemical Composition as Indicated.

The tensile strength of cast brasses (Fig. 13) decreases rapidly with increased temperatures, falling to values of less than 5000 lb. per sq. in. at 1000° F. (540° C.), according to Bengough(82). The elongation of the 70–30 brass, single-constituent type, falls rapidly to a minimum value at 800° F. (425° C.) and again increases to a

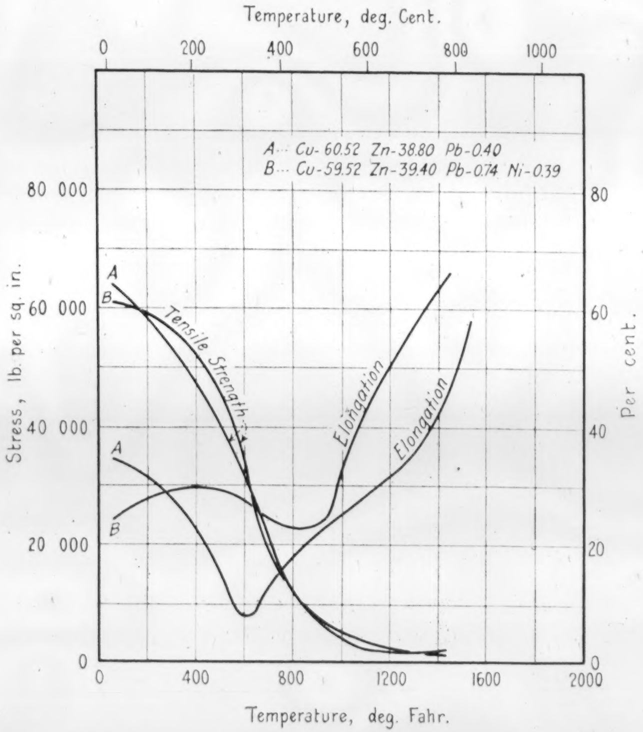

FIG. 14.—Effect of Temperature on Tensile Properties of Rolled Muntz Metal, According to Bengough(82).

Chemical Composition as Indicated.

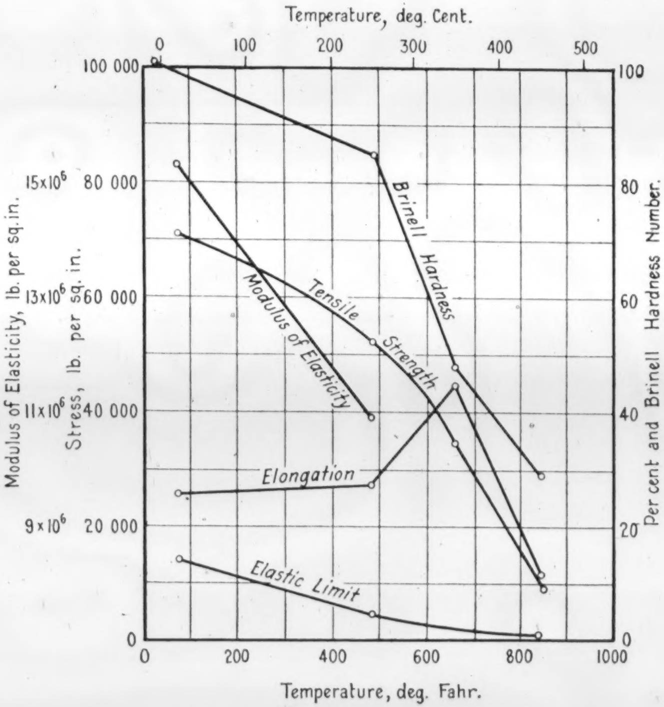

FIG. 15.—Effect of Temperature on Tensile Properties and Brinell Hardness of Modified Muntz Metal, According to Lea(**141,142**).

Chemical Composition, per cent: Cu, 58.96; Zn, 39.77; Sn, 0.56; Pb, 0.67.

maximum at 1200° F. (650° C.). The elongation of the 60–40, or two-constituent brass, increases somewhat slowly at first, but above 800° F. (425° C.) it increases rapidly to a maximum with absorption of the alpha constituent.

The tensile properties of extruded brass vary with increasing temperatures in practically the same way as for cast brass, according to both Huntington and Bengough.

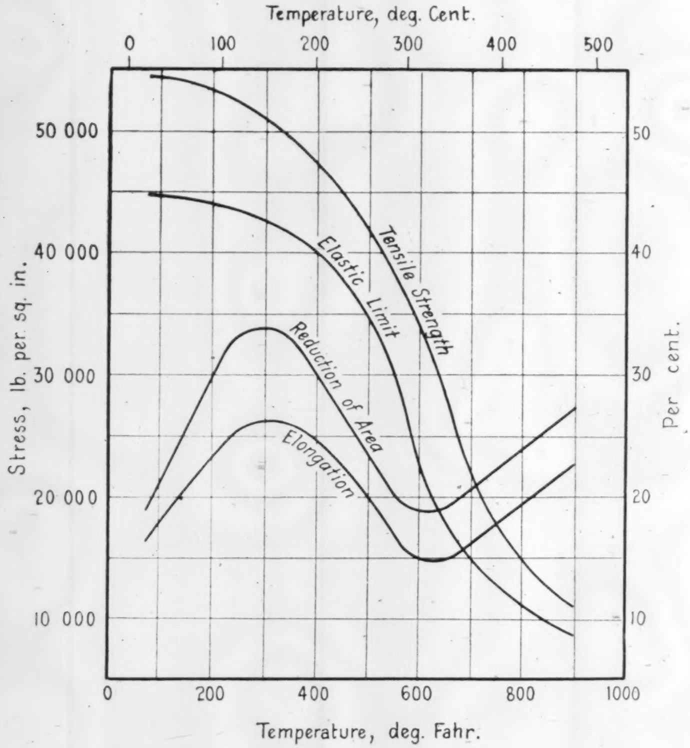

FIG. 16.—Effect of Temperature on Tensile Properties of Leaded Brass, According to Crane Co. (216).

Chemical Composition, per cent: Cu, 62.5; Zn, 35; Pb, 2.5.

Rolled brass of the Muntz metal type (Fig. 14) undergoes a somewhat slower change in tensile strength up to temperatures of 400 to 500° F. (205 to 260° C.). Above 500° F. (260° C.) the tensile strength of Muntz metal decreases to less than 10,000 lb. per sq. in. between 800 and 900° F. (425 to 480° C.), or slightly below, according to Lea (Fig. 15). Slight changes in composition, while apparently having little influence on tensile strength, may have a very marked effect on elongation as is shown in Fig. 14.

Rolled rod brass, 62.5 per cent copper and 2.5 per cent lead, according to the Crane Co. (Fig. 16) retains its tensile strength and elastic properties with very small changes up to a temperature of from 400 to 500° F. (205 to 260° C.). At temperatures above 500° F. (260° C.) tensile strength and elastic limit drop very rapidly. Compared to the *B* composition Muntz metal (Fig. 14) there appears to be very little difference in the properties of the two alloys.

Edwards and Herbert have investigated the plasticity of brasses at elevated temperatures, employing a dynamic test rather than the more commonly used static test. Plasticity is measured in terms of the indent made by the application of a 63-in-lb. blow. This is converted by the formula $\frac{7455}{d^3} = H$ to Brinell numbers, *d* being the diameter of the indent. In making the tests the samples were supported on a steel dummy and held at temperature for 15 minutes previous to the test. The time required for the blow was estimated as not exceeding 2 to 3 seconds. With this method of testing, alpha brasses show no change in plasticity up to 1100° F. (600° C.). See Figs. 17 and 18. Above 1100° F. (600° C.) they become very slightly more plastic. With an alpha-beta brass—31.12 per cent zinc, 61.9 per cent copper—a slight softening occurs below 850° F. (450° C.). Above that temperature softening is rapid. Alloys *C*, *D* and *E* (Fig. 17), with less than 60 per cent copper, show a slight decrease in plasticity up to 850° F. (450° C.), followed by a very rapid increase up to 1100° F. (600° C.). Alloys of copper and zinc, in which the beta constituent is present, become much more plastic above 850° F. (450° C.). Edwards and Herbert also observed that the degree of plasticity was much greater at 1600° F. (870° C.) if the brass was cooled down to the temperature rather than heated up to the temperature. In Fig. 18 the curves are plotted to show the effect of composition for the temperatures at which the tests were made.

Compression or crushing tests have been made on brasses at elevated temperatures by Doernickel and Trockels (Figs. 19 and 20). In these tests the work required to compress cylinders 18 mm. in diameter and 36 mm. long to 50 per cent of their length was determined. With copper the decrease in work required to produce 50 per cent compression is very nearly continuous, dropping from slightly less than 1200 ft-lb. to less than 200 ft-lb. at 1400° F. (760° C.) The curve is not unlike the tensile strength curve. The brasses show a critical point or inflection above which the work required to produce

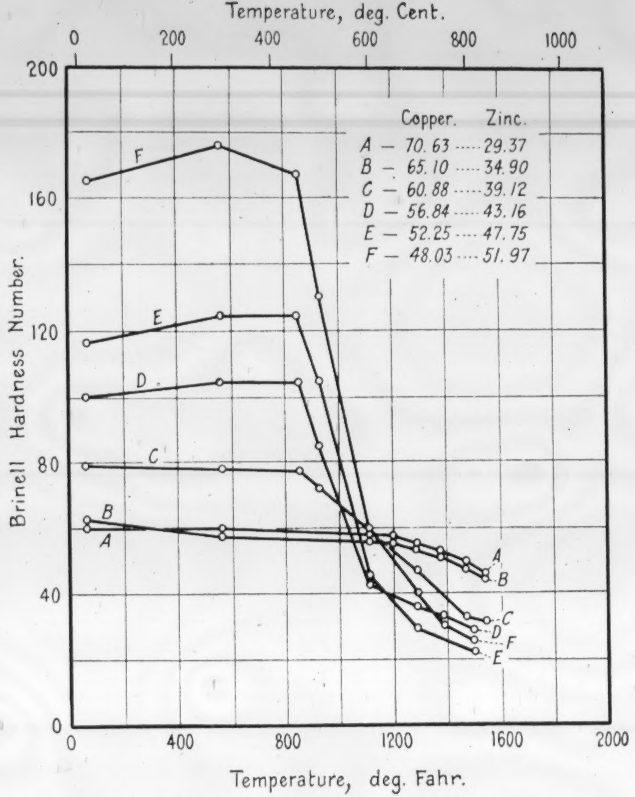

FIG. 17.—Effect of Temperature on Plasticity of Copper-Zinc Alloys, According to Edwards and Herbert(151).

Chemical Composition as Indicated.

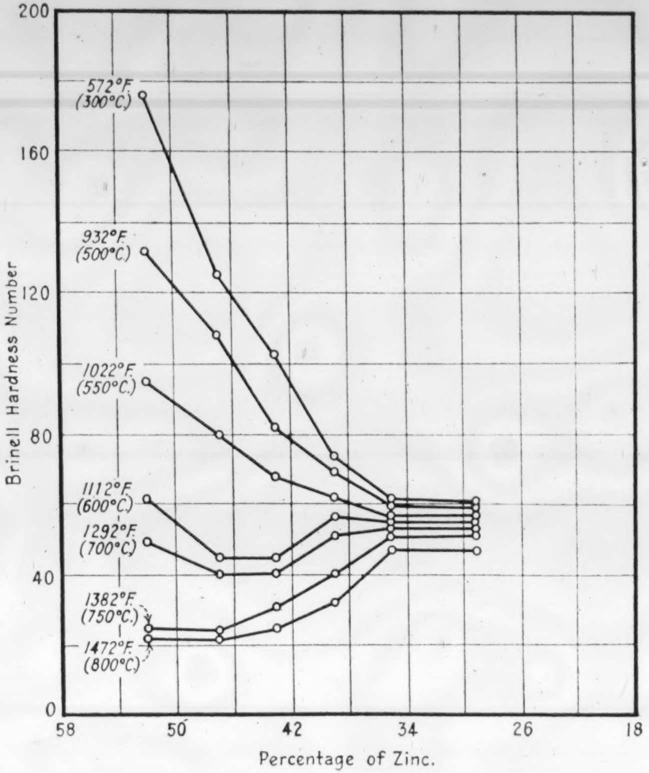

FIG. 18.—Effect of Chemical Composition on Plasticity of Copper-Zinc Alloys at Various Temperatures, According to Edwards and Herbert(151).

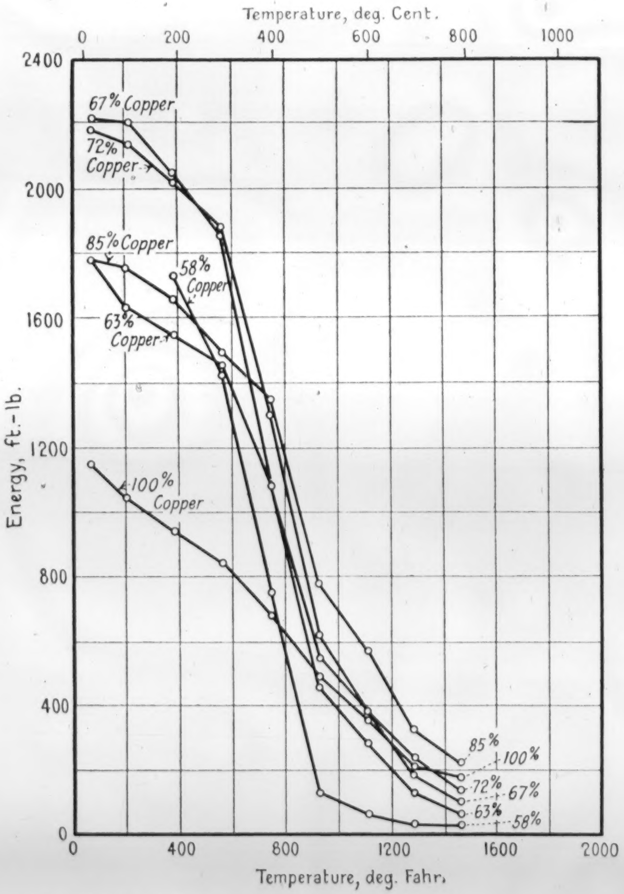

FIG. 19.—Effect of Temperature on Resistance to Compression of Copper-Zinc Alloys, According to Doernickel and Trockels (**149**).

Chemical Composition as Indicated.

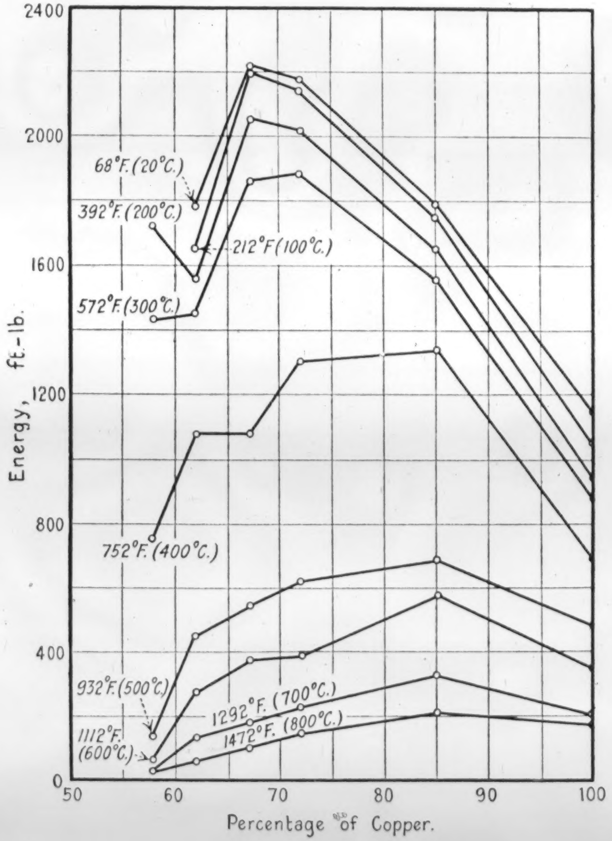

FIG. 20.—Effect of Chemical Composition on Resistance to Compression of Copper-Zinc Alloys at Various Temperatures, According to Doernickel and Trockels (**149**).

a given compression falls off rapidly. Above 932° F. (500° C.) low-zinc brasses offer the greatest resistance to crushing. Below 572° F. (300° C.) the 67 to 72-per-cent copper brasses offer the greatest resistance to crushing. Here, as with Edwards' dynamic tests, the changes due to composition are most marked at the lower temperatures.

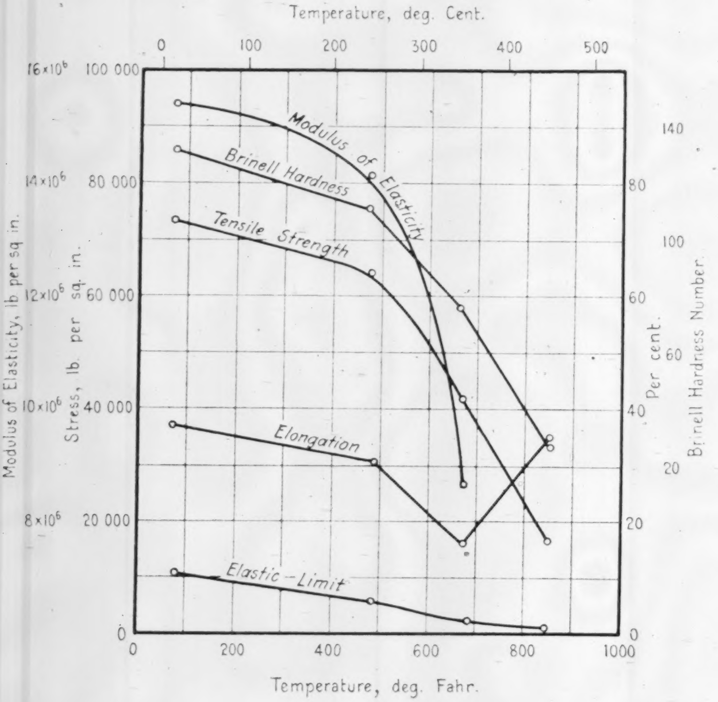

FIG. 21.—Effect of Temperature on Tensile Properties and Brinell Hardness of Delta Metal, According to Lea (**141,142**).

Chemical Composition, per cent: Cu, 58.27; Zn, 39.05; Fe, 0.13; Sn, 0.06; Ni, 2.2; Mn, 0.14; Pb, 0.15.

DELTA METAL

The tensile strength and elastic properties of Delta metal (Fig. 21) decrease slowly up to 500° F. (260° C.). Above that temperature the tensile strength decreases rapidly and the elastic limit approaches zero between 700 and 800° F. (370 to 425° C.). Delta metal is shown to retain its tensile strength somewhat better than Muntz metal (Fig. 15) up to 400° F. (205° C.) and is slightly superior at all temperatures up to 800° F. (425° C.). There appears to be little difference in the elastic properties of the two metals.

COPPER-NICKEL ALLOYS

Copper-nickel alloys, according to Lea(**141,142**), Huntington(**85**) and Bengough(**82**) (Figs. 22, 23 and 24) retain their strength very well up to temperatures of 600 to 800° F. (315 to 425° C.), depending upon the nickel content. The influence of the nickel content up to 12 per cent appears to be most marked at temperatures below 400° F. (205° C.). The elastic limit in the 2-per-cent alloys remains practically unchanged up to 600° F. (315° C.); and suggests to Lea that the copper-nickel series may offer very desirable alloys for elevated temperatures. The elastic limit has not been determined for the higher nickel contents. However, neither the 2-per-cent nor the 12-per-cent nickel alloys retains its strength to any greater extent than the 2.5-per-cent tin bronze (Fig. 6).

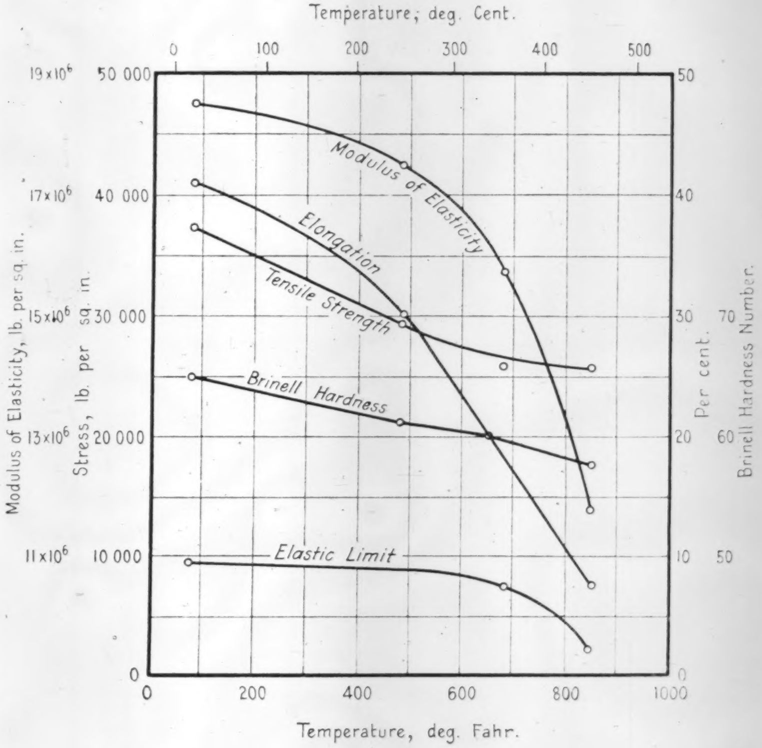

FIG. 22.—Effect of Temperature on Tensile Properties and Brinell Hardness of Copper-Nickel Alloy, According to Lea(**141,142**).

Chemical Composition, per cent: Cu, 97.80; Ni, 2.0; Al, 0.20.

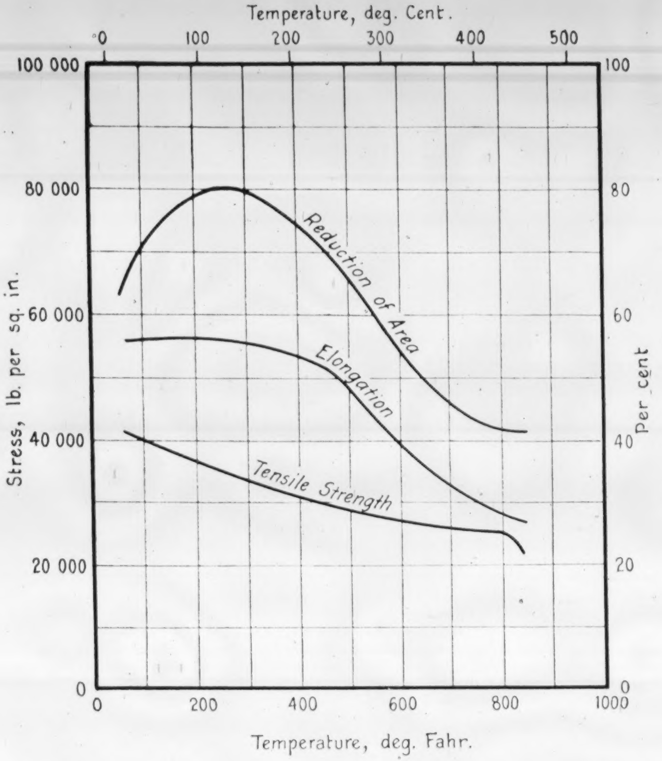

FIG. 23.—Effect of Temperature on Tensile Properties of Copper-Nickel Alloy, According to Huntington (**85**).

Chemical Composition, per cent: Cu, 88; Ni, 12.

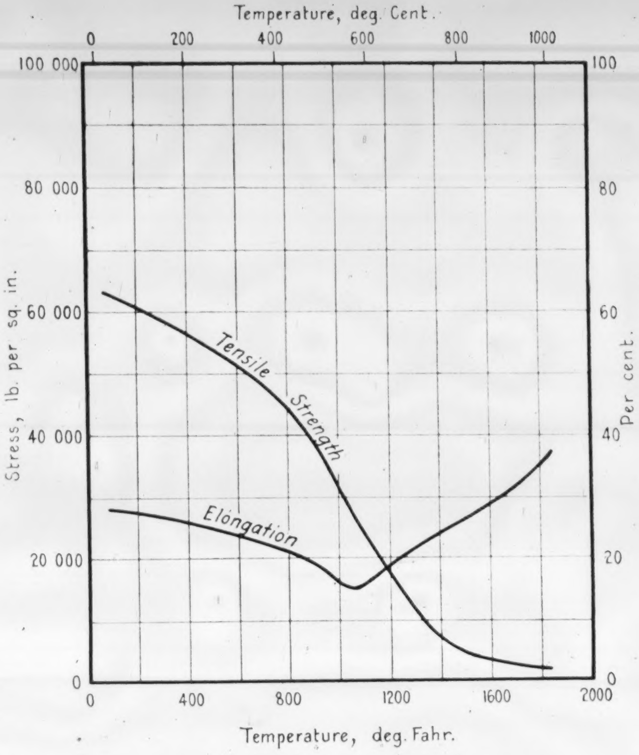

FIG. 24.—Effect of Temperature on Tensile Properties of Copper-Nickel Alloy, According to Bengough (**82**).

Chemical Composition, per cent: Cu, 79.99; Ni, 19.6; Fe and Mn, 0.41.

The 20-per-cent nickel alloy when cold rolled behaves very similarly to Muntz metal at the same temperatures as regards the tensile strength and elongation.

COPPER-TIN-ZINC-LEAD ALLOYS (STEAM BRONZE TYPE)

Alloys of this type usually decrease in both tensile strength and elongation between 500 and 600° F. (260 and 315° C.). The properties of the three alloys investigated by Bregowsky and Spring(83) are shown in Figs. 25, 26 and 27. The U. S. Navy bronze shows slightly better tensile and elastic properties up to 500° F. (260° C.) than the other two. Between 500 and 600° F. (260 and 315° C.) the tensile strength of each of the alloys has decreased to about one-half of the initial value. Above 600° F. (315° C.) the tensile strength decreases more slowly. The elongation approaches zero.

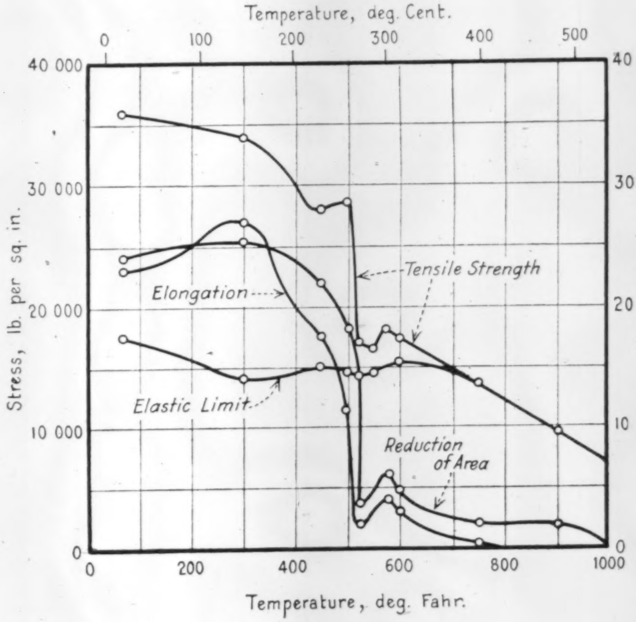

FIG. 25.—Effect of Temperature on Tensile Properties of U. S. Navy Bronze M, According to Bregowsky and Spring(83).

Chemical Composition, per cent: Cu, 86.92; Sn, 7.72; Zn, 3.62; Pb, 1.22; Fe, 0.23.

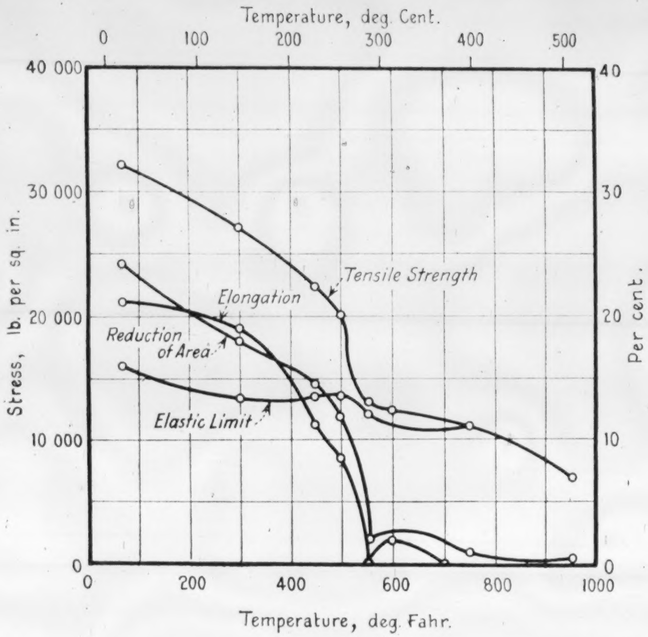

FIG. 26.—Effect of Temperature on Tensile Properties of Brass, According to Bregowsky and Spring (83).

Chemical Composition, per cent: Cu, 86.19; Sn, 5.69; Zn, 5.03; Pb, 3.02; Fe, 0.20.

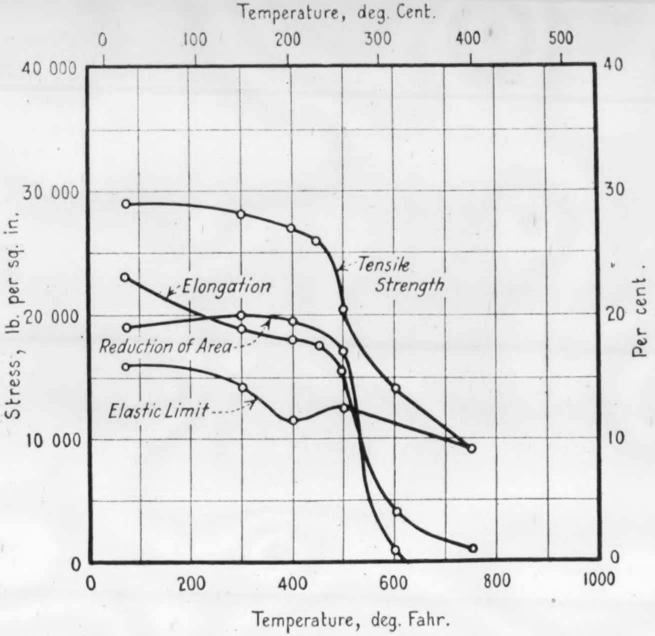

FIG. 27.—Effect of Temperature on Tensile Properties of U. S. Navy Brass S-c, According to Bregowsky and Spring (83).

Chemical Composition, per cent: Cu, 80.32; Zn, 12.80; Sn, 3.98; Pb, 2.78; Fe, 0.24.

Malcolm(212) recently presented curves for steam metal approaching the composition of the brass shown in Fig. 26. Decrease in tensile strength is slight up to 400° F. (205° C.). From 400 to 600° F. (205 to 315° C.) the decrease is rapid. From 600° F. (315° C.) up the decrease is again more gradual. The elastic limit decreases slowly from 19,800 to 8700 lb. per sq. in. at 1000° F. (540° C.). The ductility decreases somewhat more slowly.

Alloys of the leaded type invariably show loss in tensile strength and decrease in ducility when the melting point of the lead is approached, as indicated by the decrease in strength and ductility slightly below 600° F. (315° C.). The high tin alloy with low lead content shows a similar drop at 500° F. (260° C.).

NICKEL AND NICKEL CHROME

Results obtained by Sykes(146) (Fig. 28) on tests of nickel wire, purity 99.8 per cent, indicate that the tensile strength of nickel decreases slowly from atmospheric temperature—or in fact from below atmospheric temperatures—to temperatures approaching 750° F. (400° C.). Above this temperature the decrease is very rapid. Elongation also decreases from atmospheric temperatures to 575° F. (300° C.), but shows an increase at 750° F. (400° C.). Very similar results were obtained by del Regno(192), a rapid decrease in strength and increase in ducility being observed at approximately 750° F. (400° C.). Lea(142) (Fig. 29), using an impure nickel, shows a rapid decrease in tensile strength beginning between 750 and 850° F. (400 and 450° C.) with an increase in elongation at the same temperature. This constitutes an excellent example of the influence of impurities upon tensile properties.

The nickel-chrome alloy behaves similarly to the impure nickel, but decreases in its strength at lower temperatures (Fig. 29).

Some recent tests by Chevenard(170) and Le Chatelier(35) (Fig. 30) on nickel and nickel-chrome alloys indicate the necessity of greater consideration for the time element when determining properties of metals at elevated temperatures. The rate of elongation in millimeters per hour is shown for different alloys under constant load.

MONEL METAL

The tensile properties of cast monel metal presented by Bregowsky and Spring(83) (Fig. 31) are not in agreement with those recently presented by Malcolm(212) (Fig. 32). Bregowsky and Spring indicate little or no decrease in tensile strength up to 450° F. (230° C.); above

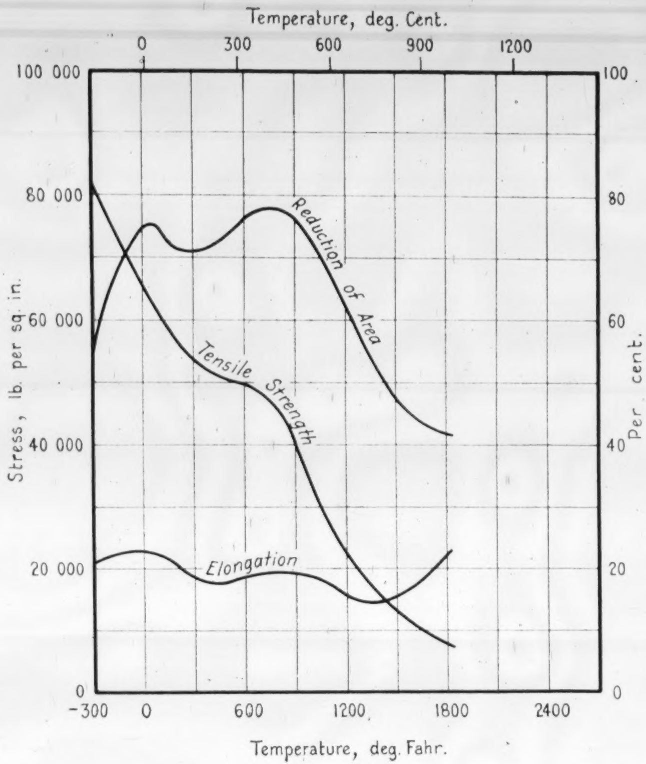

FIG. 28.—Effect of Temperature on Tensile Properties of Annealed Nickel, According to Sykes(**146**).

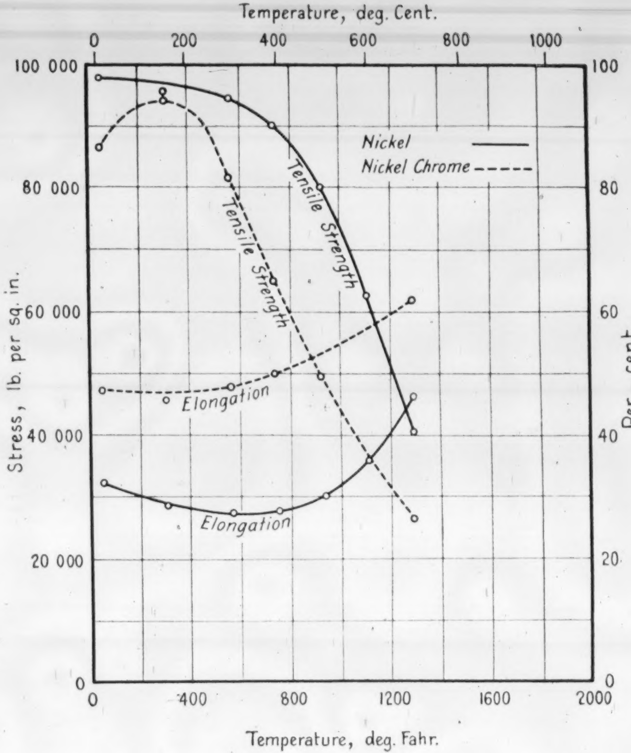

FIG. 29.—Effect of Temperature on Tensile Properties of Nickel and Nickel-Chrome, According to Lea(**142**).

Chemical Composition, per cent: *Nickel.*—Ni, 95.53; Impurities, 4.47.
Nickel-Chrome.—Ni, 59.8; Cr, 12.1; C, 0.4; Mn, 2.9; Fe, 23.7.

that temperature the tensile strength decreases rapidly to 600° F. (315° C.), and then increases slightly to 800° F. (425° C.), above which temperature the fall is rapid. Malcolm indicates the tensile strength as decreasing from atmospheric temperatures up to 400° F. (205° C.), above which the tensile strength decreases very slowly. Both show the elastic limit to decrease but slightly up to 900° F. (480° C.), although the decrease is more marked according to Bregowsky and Spring. Malcolm also disagrees with Bregowsky and Spring in regard

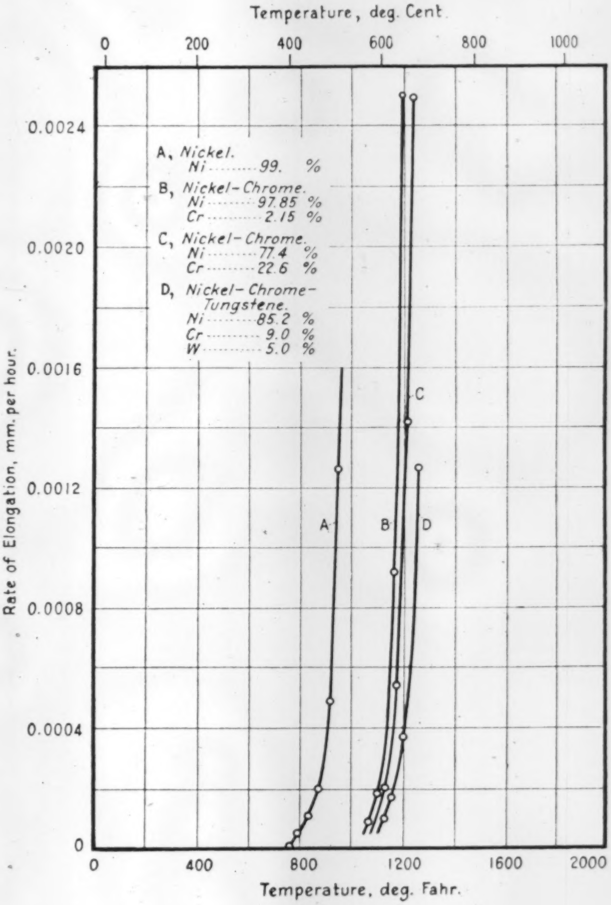

FIG. 30.—Effect of Temperature on Elongation of Nickel Alloys Under a Constant Load of 14,223 lb. per sq. in., According to Chevenard(170) and Le Chatelier(35). Chemical Composition as Indicated.

to the form of the ductility curves. Bregowsky and Spring show a maximum at 400° F. (205° C.) while Malcolm shows a minimum. Bregowsky and Spring show a reduction in ductility above 400° F. (205° C.), while Malcolm shows an increase. Malcolm's curves follow more closely the changes observed by Lea and the Allis-Chalmers Co. for worked monel metal.

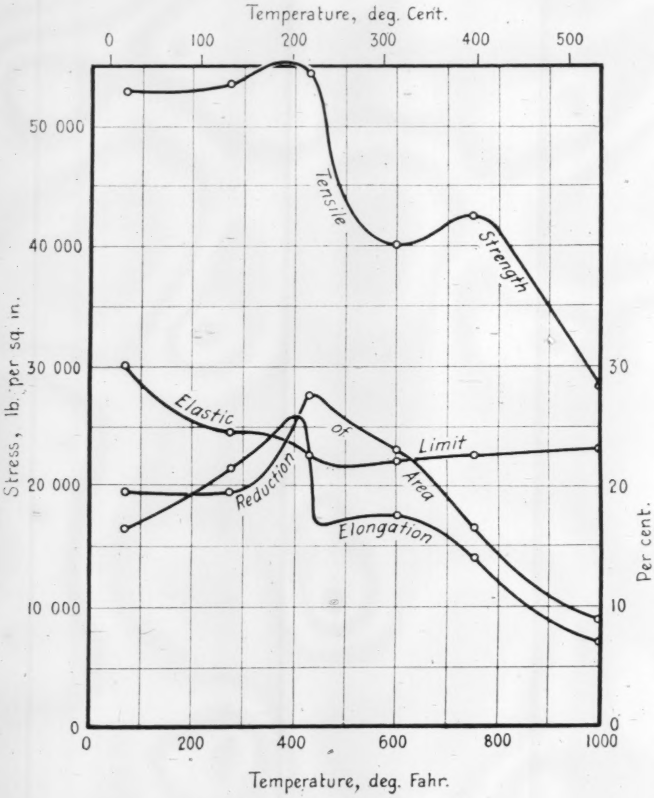

FIG. 31.—Effect of Temperature on Tensile Properties of Cast Monel Metal, According to Bregowsky and Spring (83).

Chemical Composition, per cent: Cu, 27.11; Ni, 64.79; Sn, 0.08; Pb, 0.13; Fe, 5.46; Mn, 2.33; C, 0.32.

The form of curve obtained by Bregowsky and Spring, and by Lea (142) (Fig. 33) for worked monel metal is very much the same, though there exists some doubt as to where the final drop in strength begins. All show the strength as decreasing from atmospheric temperature to 300 or 400° F. (150 or 205° C.). At

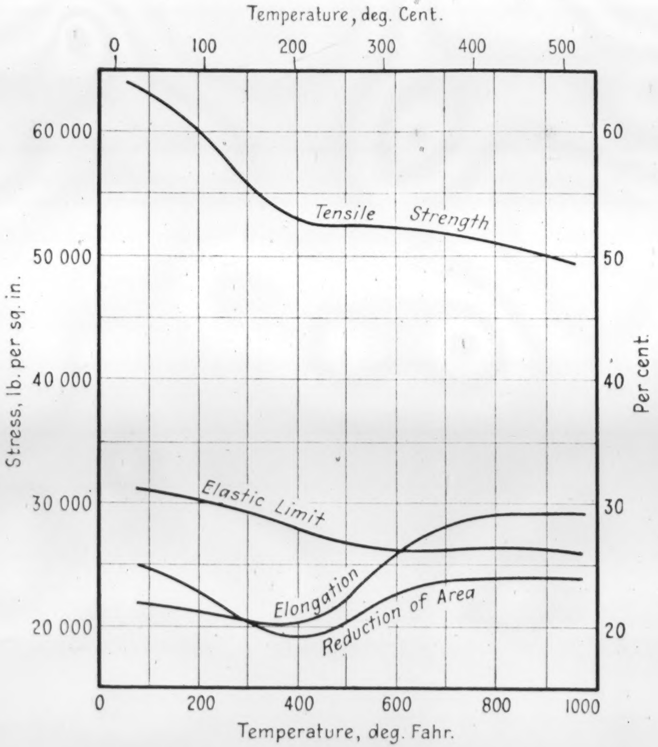

FIG. 32.—Effect of Temperature on Tensile Properties of Cast Monel Metal, According to Malcolm(212).

Chemical Composition, per cent: Cu, 29.48; Mn, 0.98; Ni, 66.63; C, 0.15; Fe, 2.36; Si, 0.40.

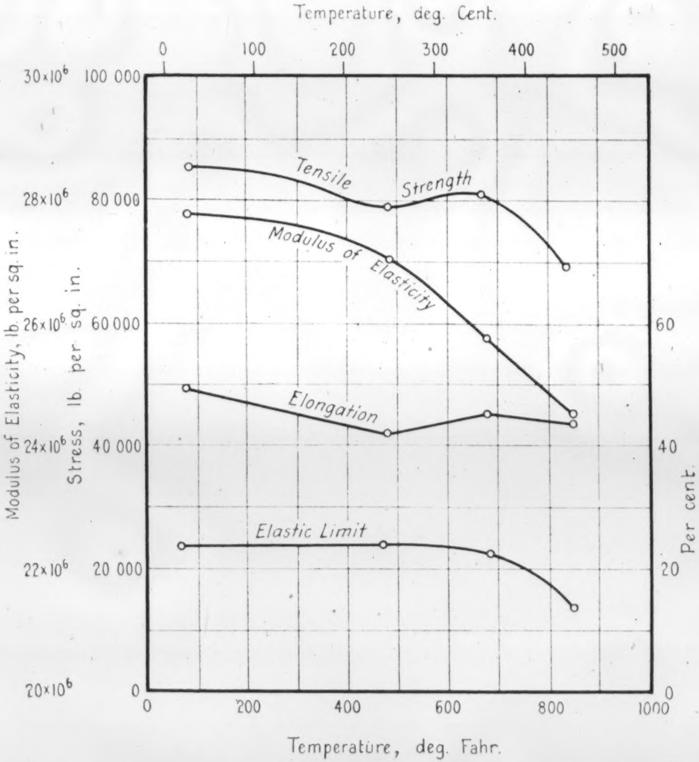

FIG. 33.—Effect of Temperature on Tensile Properties of Monel Metal, According to Lea(142).

Chemical Composition, per cent: Cu, 29.96; Ni, 66.31; Mn, 1.13; Fe, 2.24.

temperatures above 400° F. (205° C.) the tensile strength remains unchanged up to 500 to 600° F. (260 to 315° C.), up to 650 to 700° F. (345 to 370° C.) or up to 800 to 850° F. (425 to 450° C.), depending upon the investigator. According to Lea, the final and more rapid decrease in tensile strength begins between 650 and 700° F. (345 and 370° C.). The elastic limit undergoes a very marked decrease from 70 to 300° F. (21 to 150° C.) and from 600 to 800° F. (315 to 425° C.), according to Bregowsky and Spring, while Lea shows practically no

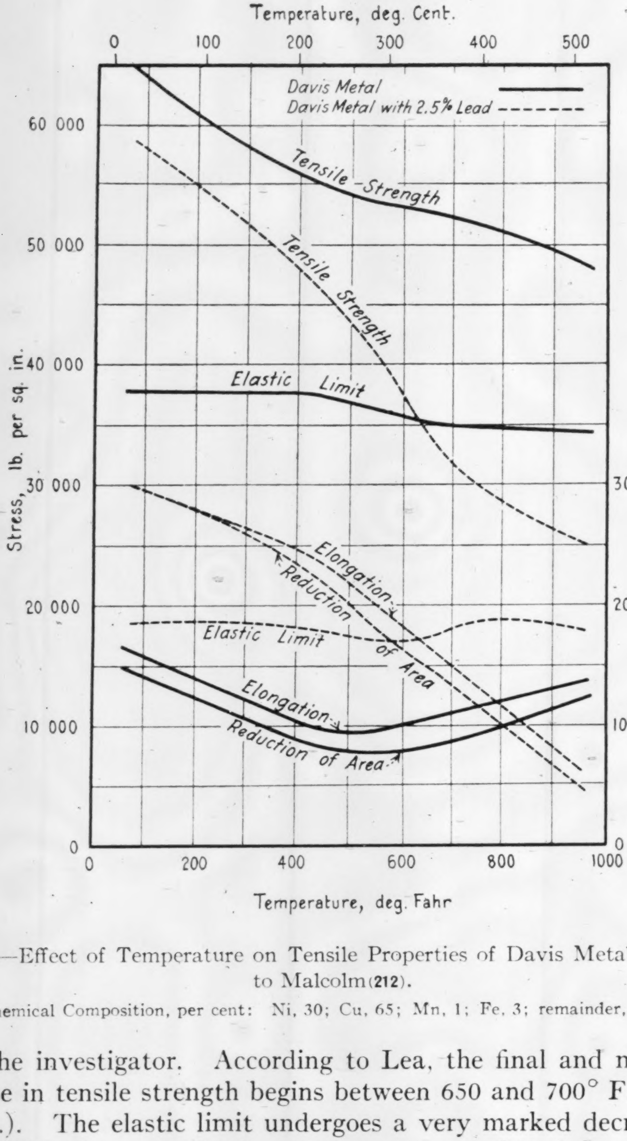

FIG. 34.—Effect of Temperature on Tensile Properties of Davis Metal, According to Malcolm(212).

Chemical Composition, per cent: Ni, 30; Cu, 65; Mn, 1; Fe, 3; remainder, C+Si.

decrease up to 700° F. (370° C.). Initial values obtained by Lea are relatively much lower than are those obtained by Bregowsky and Spring, and in fact are appreciably lower than those usually reported for monel metal.

The work of both Malcolm and Lea indicates that monel metal retains its elasticity but with relatively small decreases up to 600 to 700° F. (315 to 370° C.).

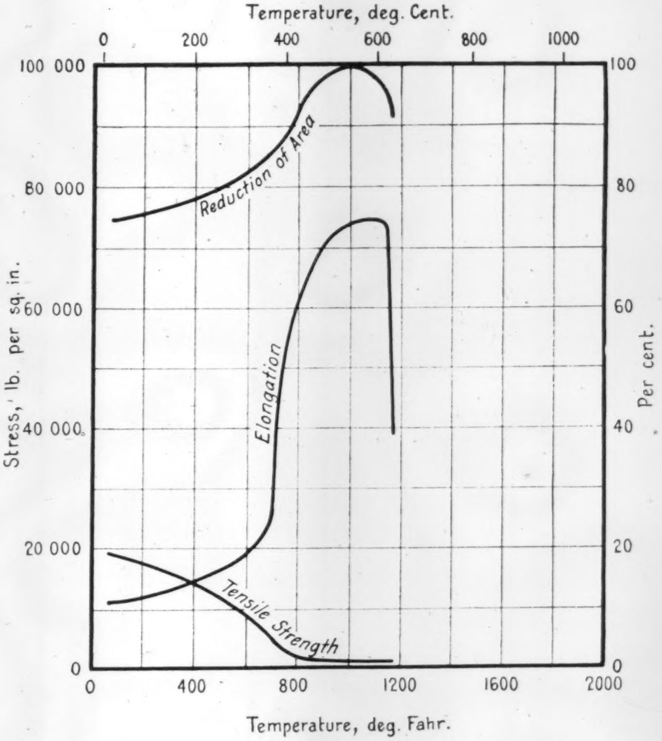

FIG. 35.—Effect of Temperature on Tensile Properties of Aluminum, According to Bengough(82)

Chemical Composition, per cent: Al, 99.56; Fe, 0.22; Si, 0.22.

DAVIS METAL

Davis Metal (Fig. 34), a copper-nickel alloy made up approximately of 30 per cent nickel, 65 per cent copper, 1 per cent manganese, 3 per cent iron, and the balance slicon and carbon, the properties of which have been very recently presented by Malcolm(212), not only retains its tensile strength at high temperatures but shows an elastic limit superior at all temperatures to monel metal. The substitution

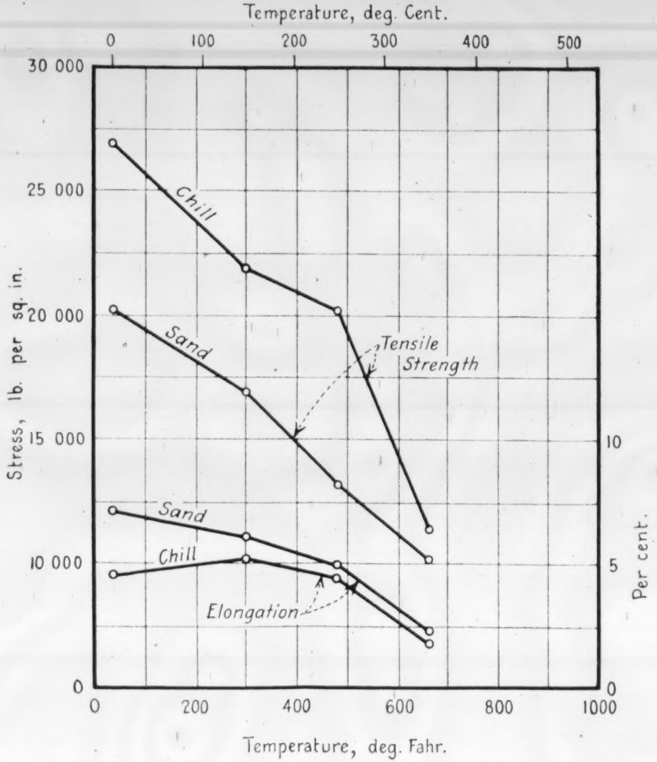

FIG. 36.—Effect of Temperature on Tensile Properties of Copper Aluminum Alloy, Chill and Sand Castings, According to Lea (187).

Chemical Composition, per cent: Al, 90; Cu, 10.

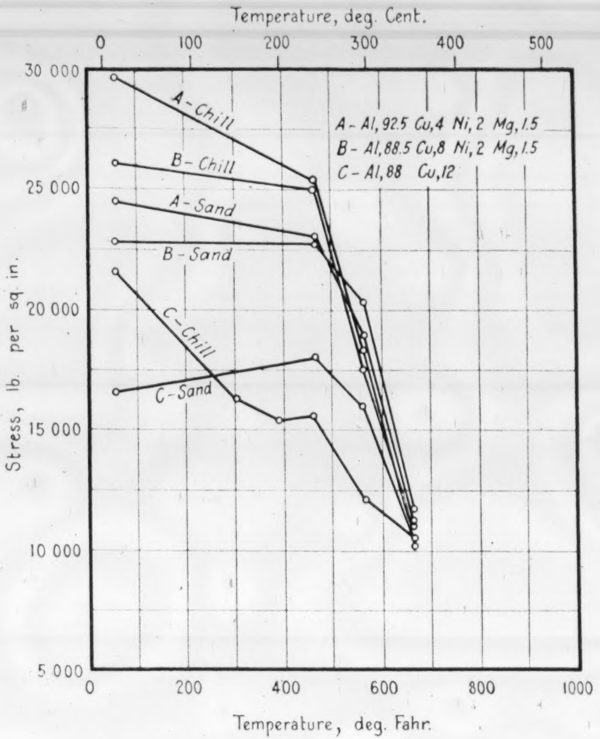

FIG. 37.—Effect of Temperature on Tensile Properties of Aluminum Alloys, Chill and Sand Castings, Eleventh Report to British Alloys Research Committee.

Chemical Composition as Indicated.

of 2.5 per cent lead (Fig. 34) decreases the strength more rapidly and cuts the elastic limit in half. The elongation and the reduction of area decrease continually with increasing temperatures.

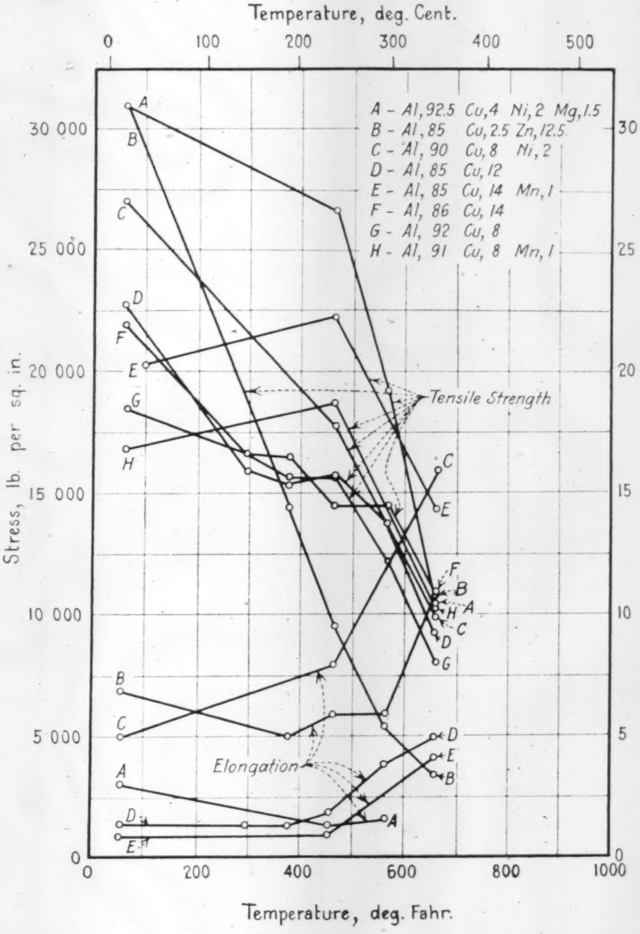

FIG. 38.—Effect of Temperature on Tensile Properties of Aluminum Alloys, Chill Castings, Eleventh Report to British Alloys Research Committee. Chemical Composition as Indicated.

ALUMINUM AND ALUMINUM ALLOYS

The tensile strength of aluminum (Fig. 35) decreases continuously to less than 2000 lb. per sq. in. at approximately 800° F. (427° C.), while the elongation increases slowly up to 700° F. (370° C.) and then suddenly goes to a maximum between 1000 and 1100° F. (540 and 600° C.), according to Bengough(82). A very striking similarity is to be noted between the behavior of aluminum and cold-rolled copper (Fig. 3).

A large amount of data relative to the behavior of aluminum alloys at elevated temperatures has been presented in the Eleventh Report to the Alloys Research Committee(161), also in the various reports of the British Light Alloys Sub-Committee, Advisory Committee for Aeronautics. Hardness tests showed that at all temperatures from 70 to 750° F. (21 to 400° C.) the alloys containing copper were harder than those free from copper. Zinc-aluminum alloys lose their hardness very rapidly, and zinc in copper-aluminum alloys causes them to become softer at higher temperatures. Manganese

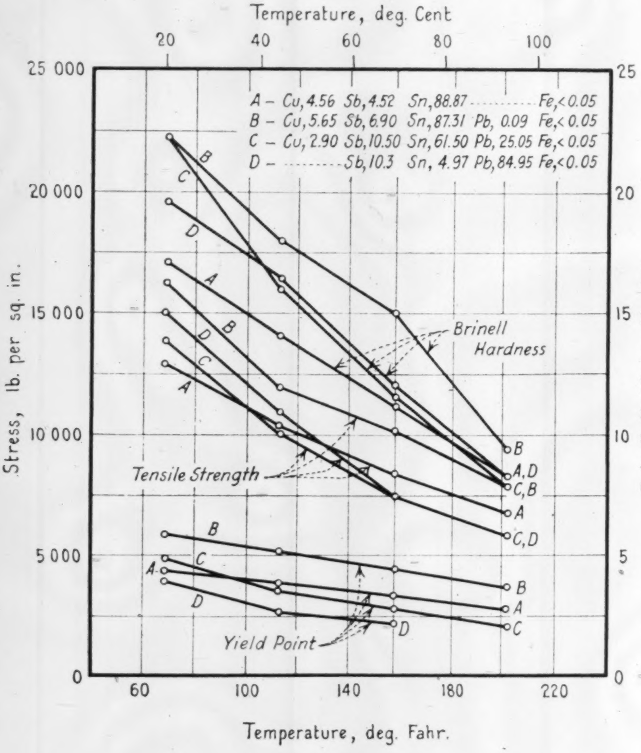

FIG. 39.—Effect of Temperature on Tensile Properties and Brinell Hardness of White Metal Bearing Alloys, According to Freeman and Woodward(152).

Chemical Composition as Indicated.

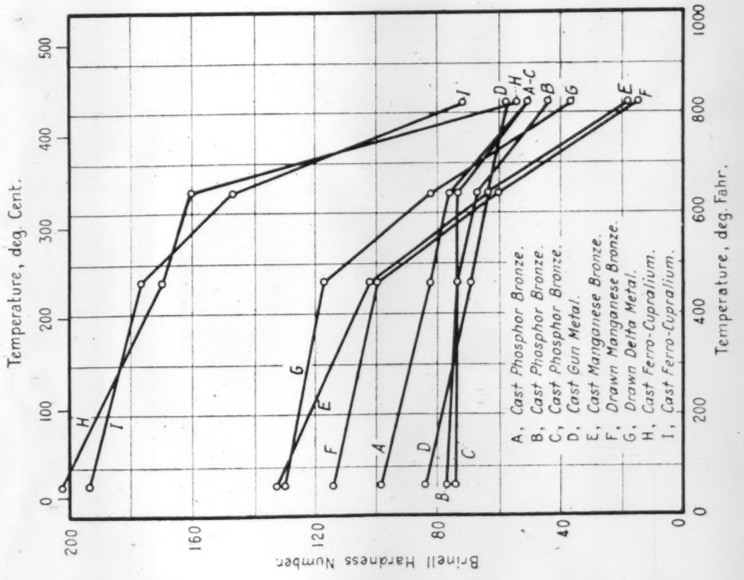

FIG 40.—Effect of Temperature on Brinell Hardness of Copper Alloys, According to Lea(141).

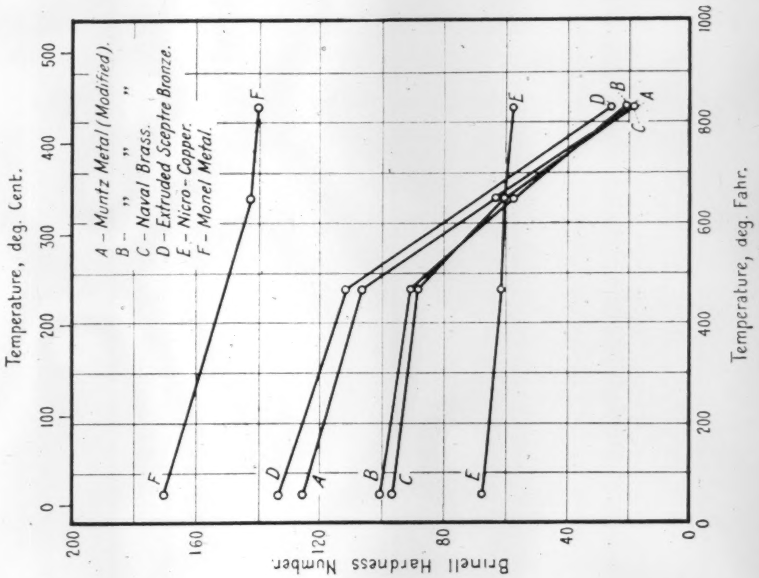

FIG. 41.—Effect of Temperature on Brinell Hardness of Copper Alloys, According to Lea(141).

and iron have the opposite effect. Tension tests on three typical aluminum alloys at low temperatures, −112° F. (−80° C.), showed no decrease in tensile properties. Impact properties of the copper-manganese-aluminum type show no change up to 480° F. (250° C.). Zinc-copper or zinc-copper-tin alloys showed a marked reduction. Duralumin decreases in resistance to impact above 150° F. (65° C.). In Figs. 36, 37 and 38 are given curves for aluminum alloys at elevated

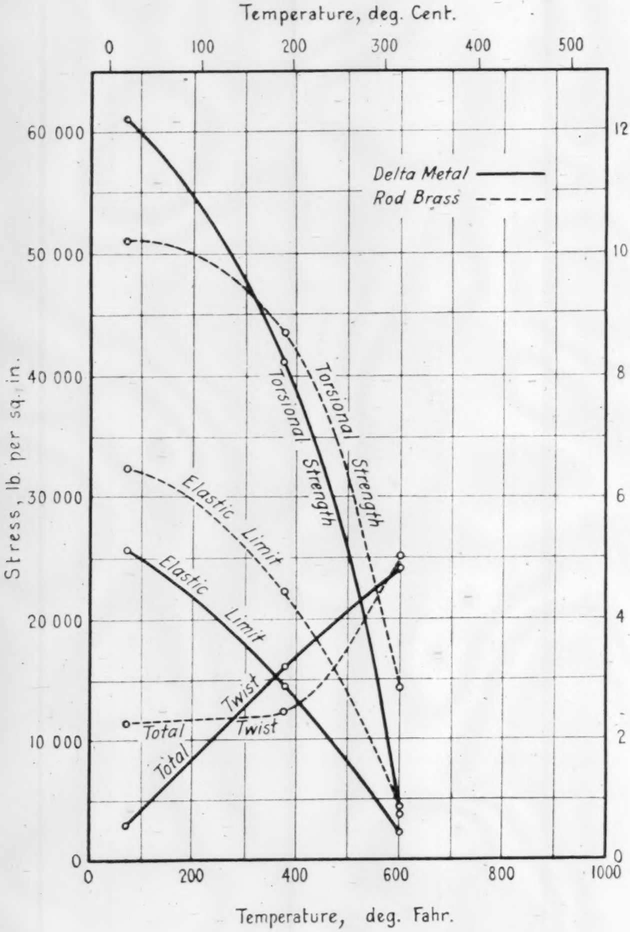

FIG. 42.—Effect of Temperature on Torsional Properties of Rod Brass and Delta Metal, According to Bregowsky and Spring (83).

Chemical Composition, per cent: *Rod Brass.*—Cu, 61.08; Zn, 35.72; Pb, 2.34; Fe, 0.42; Sn, 0.18.
Delta Metal.—Cu, 56.56; Zn, 39.36; Fe, 2.40; Sn, 0.76; Pb, 0.56; P, 0.004.

temperatures. Because of the large number of alloys which have been investigated, no attempt is made to present more than a few which may be considered typical.

Lea(187) in summing up the influence of temperature upon the properties of aluminum alloys points out that while the properties of most of the aluminum alloys change at temperatures above 480° F. (250° C.), there is little danger of aluminum pistons failing at temperatures below 650° F. (345° C.).

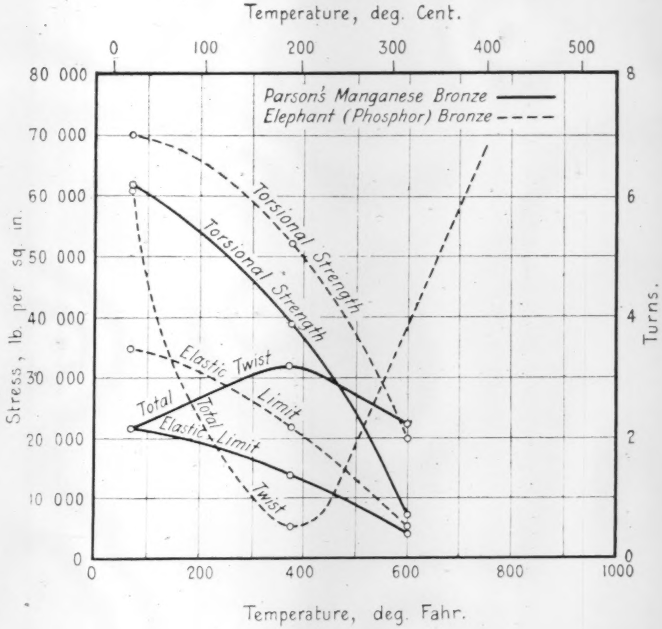

FIG. 43.—Effect of Temperature on Torsional Properties of Parson's Manganese Bronze and Elephant (Phosphor) Bronze, According to Bregowsky and Spring(83).

Chemical Composition, per cent: *Parson's Manganese Bronze.*—Cu, 59.58; Zn, 38.08; Fe, 1.22; Sn, 0.64; Al, 0.34.
Elephant (Phosphor) Bronze.—Cu, 95.52; Sn, 3.87; P, 0.307; Fe, 0.16.

BEARING METALS

Very little work relative to bearing alloys has been done at elevated temperatures. Freeman and Woodward(152), of the U. S. Bureau of Standards, have made compression and hardness tests on white metal bearing alloys (Fig. 39). The tensile strength, yield point, and Brinell hardness decrease with increasing temperatures. Alloy *B* is superior to the other alloys in the retention of strength and elasticity.

HARDNESS OF ALLOYS

Variations in hardness with increasing temperatures have been determined by Lea(141) and others. Typical hardness curves for a number of alloys according to Lea are shown in Figs. 40 and 41. Lea states that the hardness curve follows the tensile curve.

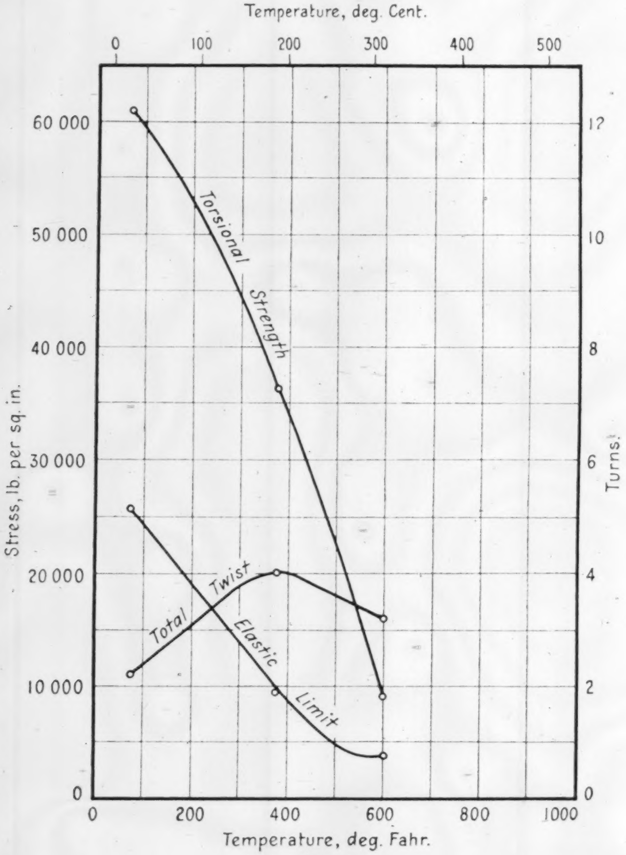

FIG. 44.—Effect of Temperature on Torsional Properties of Tobin Bronze, According to Bregowsky and Spring(83).

Chemical Composition, per cent: Cu, 59.86; Zn, 38.94; Sn, 0.80; Fe, 0.46; P, 0.0015.

TORSION TESTS

Torsion tests on five non-ferrous alloys were reported by Bregowsky and Spring(83) in 1912. The values obtained are shown in

Figs. 42, 43 and 44. Torsional strength, elastic limit and number of turns are given. No additional tests of this type have been reported in the intervening period.

The authors wish to express their appreciation to Mr. L. W. Kempf for his assistance in the preparation of the Bibliography and the physical property charts included in this paper, and to the Detroit Edison Co. for the assistance they have given in connection with the preparation of this paper.

BIBLIOGRAPHY

Reference Number — Year

(1) 1828 Tremery and Proirier-Saint-Brice, *Annales des Mines*, Vol. 3, p. 513.

(2) 1837 Fairbairn, William, "Strength and Other Properties of Iron Obtained from the Hot and Cold Blast," Report of British Association for the Advancement of Science, Vol. 6, p. 377.

(3) 1837 Report of the Committee of the Franklin Institute on the Explosion of Steam Boilers, *Dingler's Polytechnisches Journal*, Vol. 71, p. 257.

(4) 1857 Fairbairn, William, Report of British Association for the Advancement of Science, p. 215.

(5) 1862 Kirkaldy, D., "Experiments on Wrought Iron and Steel," Glasgow, Scotland, p. 65.

(6) 1863 Styffe, Knut, "Die Festigkeitseigenschaften von Eisen und Stahl," Weimar.

(7) 1871 Brockbank, William, *Nature*.

(8) 1871 Spence, Peter, *Engineering*, Vol. 2, p. 172.

(9) 1877 Pisati, G., and Saporito, C., "Experimental Researches on the Tenacity of Metals at Different Temperatures," *Memoirs*, Reale Academia dei Lincei, Vol. 1, p. 179.

(10) 1878 Huston, Charles, "The Strength and Ductility of Iron and Steel Boiler Plate at Different Temperatures," *Journal*, Franklin Institute, Vol. 75, p. 93.

(11) 1879 Huston, Charles, "The Effect of Continued and Progressively Increasing Strain upon Iron," *Journal*, Franklin Institute, Vol. 77, p. 41.

(12) 1879 Jouraffsky, Communication to London Iron and Steel Inst.

(13) 1880 Kollman, J., "Über die Festigkeitseigenschaften des Erhitzten Eisens," *Verhandlungen* des Vereins zur Beförderung des Gewerbefleisses, Vol. 59, p. 92.

(14) 1886 Bauschinger, J., "Über die Veränderung der Elasticitätsgrenze und der Festigkeit des Eisens und Stahls durch Strecken und Quetschen, durch Erwärmen und Abkühlen, und durch Oftmals Wiederholte Beanspruchung," *Mitteilungen* aus dem Mechanisch-Technischen Laboratorium der K. Polytechnischen Schule in München, Vols. 13–20.

(15) 1886 Stromeyer, C. E., "The Injurious Effect of a Blue Heat on Steel and Iron," *Proceedings*, Inst. Civil Engrs., Vol. 84, p. 114.

(16) 1889 Unwin, W. C., "The Strength of Metals at Different Temperatures," Report of British Association for the Advancement of Science.

(17) 1890 Howard, J. E., "Physical Properties of Iron and Steel at Higher Temperature, Report of Experiments at Watertown Arsenal," *Iron Age*, Vol. 45, p. 585.

REFERENCE NUMBER	YEAR	
(18)	1890	Martens, A., "Untersuchungen über den Einfluss der Wärme auf die Festigkeitseigenschaften des Eisens," *Mitteilungen* aus den kgl. Versuchsanstalten zu Berlin, Vol. 8, p. 159.
(19)	1891	Howe, H. M., "The Metallurgy of Steel."
(20)	1893	Rudeloff, M., "Untersuchungen über den Einfluss der Wärme auf die Festigkeitseigenschaften von Metallen," *Mitteilungen* aus den kgl. Versuchsanstalten zu Berlin, Vol. 11, p. 292.
(21)	1895	Charpy, G., "Étude sur le Trempe de l'Acier," ***Bulletin,*** Société d'Encouragement pour l'Industrie Nationale, Vol. 94, p. 660.
(22)	1895	Rudeloff, M., "Untersuchungen über den Einfluss der Kälte auf die Festigkeitseigenschaften von Eisen und Stahl," *Mitteilungen* aus den kgl. Versuchsanstalten zu Berlin, Vol. 13, p. 197.
(23)	1895	"The Strength of Metals at High Temperatures," ***Engineering,*** Vol. 60, p. 186.
(24)	1896	Carpenter, R. C., "Effect of Temperature on Strength of Wrought Iron and Steel," *Transactions,* Am. Soc. Mechanical Engrs., Vol. 17, p. 198.
(25)	1896	Charpy, G., "Étude sur le Trempe de l'Acier," ***Bulletin,*** Société d'Encouragement pour l'Industrie Nationale, Series V, Vol. 1, p. 386.
(26)	1896	Kurzwernhart, A., "The Influence of a Blue Heat," ***Stahl und Eisen,*** Vol. 16, p. 849.
(27)	1898	Rudeloff, M., "Einfluss der Wärme, Chemischen Zusammensetzung und Mechanischen Bearbeitung auf die Festigkeitseigenschaften der Kupfer," *Mitteilungen* aus den kgl. Versuchsanstalten zu Berlin, Vol. 16, p. 171.
(28)	1898	Svedelius, G. E., "Length Variation of Iron and Steel During Recalescence," *Philosophical Magazine,* Vol. 46, p. 173.
(29)	1899	Charpy, G., "Étude sur l'Influence de la Température sur les Propriétés des Alliages Métalliques," ***Bulletin,*** Société d'Encouragement pour l'Industrie Nationale, Vol. 98, p. 191.
(30)	1899	Le Chatelier, H., "Transformation of Iron and Steel," *Comptes Rendus,* Vol. 129, pp. 279, 331.
(31)	1899	Osmond, F., "Alloys of Iron and Nickel," *Comptes Rendus,* Vol. 128, p. 304.
(32)	1899	Unwin, W. C., Report of British Association for the Advancement of Science.
(33)	1900	Bach, C., "Versuche über die Abhängigkeit der Festigkeit und Dehnung der Bronze von der Temperatur," ***Zeitschrift,*** Verein deutscher Ingenieure, Vol. 44, p. 179.
(34)	1900	Le Blant, "Les Entretoises de Foyers de Locomotives," Congrés International des Methodes d'Essai, Vol. 2, p. 268.

REFERENCE NUMBER	YEAR	
(35)	1900	Le Chatelier, A., "L'Influence du Temps et de la Température sur les Propriétés Mecaniques et les Essais des Métaux, "Congrés International des Methodes d'Essai, Vol. 2, p. 1.
(36)	1900	Rudeloff, M., "Einfluss der Wärme auf die Festigkeitseigenschaften der Metalle," *Mitteilungen* aus den kgl. Versuchsanstalten zu Berlin, Vol. 18, p. 293.
(37)	1900–1906	Muir, J., "On the Overstraining of Iron," *Philosophical Transactions*, Royal Society of London, A 193, p. 1; *Ibid.*, A 198, p. 1; *Proceedings*, A 77, p. 277.
(38)	1901	Bach, C., "Weitere Versuche über die Abhängigkeit der Zugfestigkeit und Bruchdehnung der Bronze von der Temperatur," *Zeitschrift*, Verein deutscher Ingenieure, Vol. 45, p. 1477.
(39)	1901	Le Chatelier, *Baumaterialienkunde*, Vol. 6, pp. 157, 173, 209, 229, 247.
(40)	1901	Ridsdale, C. H., "The Correct Treatment of Steel," *Journal*, Iron and Steel Inst., No. 2, p. 52.
(41)	1902	Le Chatelier, *Baumaterialienkunde*, Vol. 7, pp. 13, 80, 137, 152, 171, 185.
(42)	1902	Webb, F. W., "Locomotive Firebox Stays," *Proceedings*, Inst. Civil Engrs., Vol. 150, p. 87.
(43)	1902–1903	Charpy, G., and Grenet, L., "Dilatation of Steel at High Temperatures," *Comptes Rendus*, Vol. 134, p. 540; Vol. 136, p. 92.
(44)	1903	Bach, C., "Versuche über die Festigkeitseigenschaften von Stahlguss bei Gewöhnlicher und Höherer Temperatur," Verein deutscher Ingenieure, *Zeitschrift*, Vol. 47, Part II, p. 1762.
(45)	1903	Guillaume, C. E., "Changes in Nickel Steels," *Comptes Rendus*, Vol. 136, p. 356.
(46)	1903	Guillaume, C. E., "Dilatation of Nickel Steels," *Comptes Rendus*, Vol. 136, p. 303.
(47)	1903	Guillaume, C. E., "Non-Expansive Alloys," *Metallographist*, Vol. 6, p. 162.
(48)	1903	Stribeck, *Zeitschrift*, Verein deutscher Ingenieure, Vol. 47, p. 559.
(49)	1904	Bach, C., "Versuche über die Festigkeitseigenschaften von Flusseisenblech bei Gewöhnlicher und Höherer Temperatur," *Zeitschrift*, Verein deutscher Ingenieure, Vol. 48, p. 1300.
(50)	1904	Bach, C., "Versuche über die Festigkeitseigenschaften von Sthalguss bei Gewöhnlicher und Höherer Temperatur," *Zeitschrift*, Verein deustcher Ingenieure, Vol. 48, Part I, p. 385.
(51)	1904	Outerbridge, A. E., Jr., "The Mobility of Molecules of Cast Iron," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. 35, p. 223.
(52)	1904	Stribeck, *Zeitschrift*, Verein deutscher Ingenieure, Vol. 48, p. 897.

REFERENCE NUMBER	YEAR	
(53)	1905	Brinell, J. A., "Researches on the Comparative Hardness of Acid and Basic Open-Hearth Steel at Various Temperatures by Means of Ball Testing," *Iron and Steel Magazine*, Vol. 9, p. 16.
(54)	1905	Hadfield, R. A., "Experiments Relating to the Effect on Mechanical and Other Properties of Iron and Its Alloys Produced by Liquid Air Temperatures," *Journal*, Iron and Steel Inst., Vol. 67, p. 147.
(55)	1905	Hopkinson, B., and Rogers, F., "The Elastic Properties of Steel at High Temperatures," *Proceedings*, Royal Society of London, Vol. 76, p. 419.
(56)	1906	Charpy, G., "Sur l'Influence de la Température sur la Fragilité des Métaux," *Essais des Matériaux de Construction*, Brussels, A 17f.
(57)	1907	Rosenhain, W., *Proceedings*, Inst. Mechanical Engrs. (British), p. 291.
(58)	1908	Robin, F., "La Dureté à Chaud des Aciers," *Revue de Métallurgie, Mémoires*, 5, p. 893; 6, p. 180.
(59)	1909	Guillet, L., and Revillon, L., "Expériences sur l'Essai au Choc à Températures Variables," *Revue de Métallurgie, Mémoires*, 6, p. 94.
(60)	1909	Guillet and Revillon, "Impact Tests at Variable Temperatures," *Proceedings*, Int. Assoc. Testing Mats., Fifth Congress, Copenhagen, Vol. I, 1908–10, No. III_4.
(61)	1909	Hollis, I. N., "The Effect of Superheated Steam on Cast Iron and Steel," *Engineering News*, Vol. 62, p. 700.
(62)	1909	Kürth, A., "Untersuchungen über den Einfluss der Wärme auf die Härte der Metalle," *Zeitschrift*, Verein deutscher Ingenieure, Vol. 53, pp. 85, 209.
(63)	1909	Robin, F., "La Dureté des Aciers aux Basses Températures," *Revue de Métallurgie, Mémoires*, 6, p. 162.
(64)	1909	Rudeloff, M., "The Influence of Increased Temperature on the Mechanical Qualities of Metals," *Proceedings*, Int. Assoc. Testing Mats., Fifth Congress, Copenhagen, Vol. I, 1908–10, No. VI_1.
(65)	1909–1911	Rugan, H. F., and Carpenter, H. C. H., "The Growth of Cast Irons after Repeated Heatings," *Journal*, Iron and Steel Inst., Part 2, p. 29; continued by Carpenter, 1911, Part I, p. 196.
(66)	1910	Cary, A. A., "The Effect of Superheated Steam on Cast Iron and Steel," *Iron Age*, Vol. 85, p. 800.
(67)	1910	Collins, B. R. T., "Cast-Iron or Steel Fittings for Superheated Steam," *Castings*, Vol. 6, p. 200.
(68)	1910	Mann, A. S., "Cast-Iron Valves and Fittings for Superheated Steam," *Foundry*, Vol. 35, p. 198.
(69)	1910	Memmler, K., and Schob, A., "Elektrische Beheizung von Probestäben und Wärme-Messung bei den Dauerversuchen mit Rohrmaterialien," *Mitteilungen* aus dem kgl. Materialprüfungsamt, Vol. 28, p. 307.

REFERENCE NUMBER	YEAR	
(70)	1910	Miller, E. F., "Effect of Superheated Steam on the Strength of Cast Iron, Gun Iron and Steel," *Foundry*, Vol. 35, p. 200.
(71)	1910	Robin, F., "The Resistance of Steels to Crushing at all Temperatures," *Carnegie Scholarship Memoirs* (Iron and Steel Inst.), Vol. 2, p. 70.
(72)	1910	Robin, F., "Variation de la Resistance à l'Écrasement des Aciers en Fonction de la Température, Relation entre les Propriétés Statiques et Dynamiques des Aciers," *Comptes Rendus*, Vol. 151, p. 710.
(73)	1910	Rosenhain, W., *Proceedings*, Inst. Mechanical Engrs. (British), p. 200.
(74)	1910	Rosenhain, W., and Humfrey, J. C. W., "The Crystalline Structure of Iron at High Temperatures," *Proceedings*, Royal Society of London, Series A, Vol. 83, p. 200.
(75)	1910	Unwin, W. C., "The Testing of Materials of Construction," p. 327.
(76)	1910	"Rapid Deterioration of Steel Work from Corrosive Action of Locomotive Gas, McCallie Avenue Bridge, Chattanooga, Tenn.," *Engineering News*, Vol. 63, p. 65.
(77)	1911	Friend, J. A. N., and Brown, J. H., "Action of Salt Solutions and of Sea Water on Iron at Various Temperatures," *Journal*, Chemical Society, London, Vol. 99, Part 1, p. 1302.
(78)	1911	Friend, J. A. N., Hull, T. E., and Brown, J. H., "Action of Steam on Iron at High Temperatures," *Journal*, Chemical Society, London, Vol. 99, Part 1, p. 969.
(79)	1911	Hughes, "Non-Ferrous Metals in Railway Work," *Journal*, Inst. of Metals, Vol. 6, p. 74.
(80)	1912	Batson, R. G., *Collected Researches*, National Physical Laboratory, Vol. 8.
(81)	1912	Baykoff, "Metallography and Strains of Steel at High Temperatures," *Engineering*, Vol. 93, p. 411.
(82)	1912	Bengough, G. D., "A Study of Properties of Alloys at High Temperatures," *Journal*, Inst. of Metals, Vol. 7, p. 123.
(83)	1912	Bregowsky, I. M., and Spring, L. W., "The Effect of High Temperature on the Physical Properties of Some Alloys," *Proceedings*, Int. Assoc. Testing Mats., Sixth Congress, New York, Vol. II, Part 2, First Section, VII_1.
(84)	1912	Campbell, W., and Glassford, J., "The Constitution of Cast Iron and the Effects of Superheated Steam," *Proceedings*, Int. Assoc. Testing Mats., Sixth Congress, New York, Vol. II, Part 2, First Section, II_{19}.
(85)	1912	Huntington, A. K., "The Effect of Temperatures Higher than Atmospheric on Tensile Tests of Copper and Its Alloys and a Comparison with Wrought Iron and Steel," *Journal*, Inst. of Metals, Vol. 8, p. 126.
(86)	1912	Robin, F., "On Several Mechanical Properties of Metals in the Hot State," *Proceedings*, Int. Assoc. Testing Mats., Sixth Congress, New York, Vol. II, Part 2, First Section, VII_2.

REFERENCE NUMBER	YEAR	
(87)	1912	Robin, F., "The Effect of Temperature on the Frequency and Duration of Sound on Tuning Forks," *Journal de Physique*, Vol. 5, Series 2, p. 298.
(88)	1912	Robin, F., "Variations of the Hardness of Steel as a Temperature Function," *Proceedings*, Int. Assoc. Testing Mats., Seventh Congress, New York, Vol. 2, Part II, First Section, VII_3.
(89)	1912	National Physical Laboratory, *Notes*.
(90)	1912	"The Influence of Increased Temperature on the Strength of Certain Metals and Alloys," *Chemical and Metallurgical Engineering*, Vol. 10, p. 160.
(91)	1913	Charpy, G., and Cornu, A., "Transformation of Iron-Silicon Alloys," *Comptes Rendus*, Vol. 156, p. 1240.
(92)	1913	Goerens, P., and Hartel, G., "Über die Zähigkeit des Eisens bei Verschiedenen Temperaturen," *Zeitschrift für Anorganische Chemie*, Vol. 81, p. 130.
(93)	1913	Rosenhain, W., and Humfrey, J. C. W., "The Tenacity, Deformation, and Fracture of Soft Steel at High Temperatures," *Journal*, Iron and Steel Inst., Vol. 87, p. 219.
(94)	1913	Schultz, "Neue Versuche und Erfahrungen mit Turbinenschaufelmaterial für Hohe Temperaturen," *Die Turbine*, Vol. 9, pp. 225, 243, 266.
(95)	1913	Schultz, "New Researches with Turbine Materials for High-Temperature Steam and Gas Turbines," *Die Turbine*, Vol. 13, p. 14.
(96)	1914	Bengough and Hanson, "Copper at High Temperatures," *Journal*, Inst. of Metals, Vol. 12, p. 56.
(97)	1914	Charpy, G., "Sur la Fragilité Produite dans les Fers et Aciers par Deformation à Differentes Températures," *Comptes Rendus*, Vol. 158, p. 311.
(98)	1914	Dewrance, J., "Bronze," *Journal*, Inst. of Metals, Vol. 11, p. 214.
(99)	1914	Dreisen, J., "Thermal Expansion and Rate of Solution of Iron-Carbon Alloys," *Ferrum*, Vol. 11, pp. 129, 161.
(100)	1914	Guillet, L., "Alloys having Remarkable Properties at Very High or Very Low Temperatures," *Revue de Métallurgie, Mémoires*, Vol. 11, p. 969.
(101)	1914	Hansen, C. A., "Method of Making Tungsten Filaments" (abstract), *Journal*, Inst. of Metals, Vol. 11, p. 294.
(102)	1914	Huntington, A. K., "The Effect of Temperatures Higher than Atmospheric on Tensile Tests of Copper and Its Alloys and a Comparison with Wrought Iron and Steel," *Journal*, Inst. of Metals, Vol. 12, p. 234.
(103)	1914	Lea, F. C., and Crowther, O. H., "The Change of the Modulus of Elasticity and of Other Properties of Metals with Temperature," *Engineering*, Vol. 98, p. 487.
(104)	1914	Perrine, H., and Spencer, C. B., "The Physical Properties of Steel and Cast-Iron Bars Broken at Different Temperatures," Columbia University, School of Mines, *Quarterly*, Vol. 35, p. 194.

Reference Number	Year	
(105)	1915	Bach, C., and Baumann, R., "Festigkeitseigenschaften und Gefügebilder der Konstruktionsmaterialien," Berlin, pp. 8, 82, 87.
(106)	1915	Harrison, "Variation of Elasticity of Nickel with Temperature," *Proceedings*, Physical Society, Vol. 27, p. 8.
(107)	1915	Huntington, A. K., "The Effect of Heat and Work on the Mechanical Properties of Metals," *Journal*, Inst. of Metals, Vol. 13, p. 23.
(108)	1915	Koch and Dannecker, "Die Elastizität einiger Metalle und Legierungen bis zu Temperaturen die ihrem Schmelzpunkt Naheliegen," *Annalen der Physik*, Vol. 47, p. 197.
(109)	1915	Ludwik, P., "Festigkeitseigenschaften und Molekularhomologie der Metalle bei Höheren Temperaturen," *Zeitschrift*, Verein deutscher Ingenieure, Vol. 59, p. 657.
(110)	1915	Rosenhain, W., "An Introduction to Physical Metallurgy."
(111)	1916	Hurst, J. E., "The Growth of Internal Combustion Engine Cylinders," *Engineering*, Vol. 102, p. 97.
(112)	1916	Ludwik, P., "Über die Änderung der inneren Reibung der Metalle mit der Temperatur," *Zeitschrift für Physikalische Chemie*, Vol. 91, p. 232.
(113)	1916	Reinhold, O., "The Mechanical Properties of Steel at High Temperatures," *Ferrum*, Vol. 13, pp. 97, 116, 129.
(114)	1916	Stead, J. E., "Notes on the Effect of Blast-Furnace Gases on Wrought Iron," *Journal*, Iron and Steel Inst., Vol. 94, p. 249.
(115)	1916	Stead, J. E., "Notes on Nickel Steel Scale," *Journal*, Iron and Steel Inst., Vol. 94, Part 2, p. 243.
(116)	1917	Epps, F. A., and Jones, E. O., "The Influence of High Temperatures upon Elastic and Tensile Properties of Wrought Iron," *Chemical and Metallurgical Engineering*, Vol. 17, p. 67.
(117)	1917	Honda, K., "On the Thermal Expansion of Different Kinds of Steel at High Temperatures," *Science Reports*, Tohoku Imperial University, Vol. 6, p. 203.
(118)	1917	Parr, S. W., "The Embrittling Action of Sodium Hydroxide on Soft Steel," *Bulletin No. 94*, Engineering Experiment Station, University of Illinois.
(119)	1917	Percy, E. N., "Effect of Temperature on Structural Materials," *Machinery*, Vol. 23, p. 594.
(120)	1918	Edwards, C. A., "A Law Governing the Resistance to Penetration of Metals when Tested by Impact with 10-mm. Ball and a New Hardness Scale in Energy Units," *Journal*, Inst. Mechanical Engrs. (British).
(121)	1918	Gordon, F. F., *et al.*, "Steel for Internal Combustion Engine Valves," British Patent 133,168.
(122)	1918	Johnson, F., "The Influence of Impurities on the Mechanical Properties of Gun Metal," *Journal*, Inst. of Metals Vol. 20, p. 167.

REFERENCE NUMBER YEAR

(123) 1919 Aitchison, L., "Valve Failures and Valve Steels in Internal Combustion Engines," *Engineering*, Vol. 108, p. 799; *Proceedings*, Inst. Automobile Engrs. (British), Vol. 14, p. 31.

(124) 1919 Chevenard, P., "Sur la Viscosité des Aciers aux Températures Élevées," *Comptes Rendus*, Vol. 169, p. 712.

(125) 1919 Fettweis, "Über die Blaubrüchigkeit und das Altern des Eisens," *Stahl und Eisen*, Vol. 39, pp. 1, 34.

(126) 1919 Honda, K., and Matsushita, T., "On Some Physical Constants of Tungsten Steel," *Science Reports*, Tohoku Imperial University, Vol. 8, p. 89.

(127) 1919 Jeffries, Zay, "Effect of Temperature, Deformation, and Grain Size on the Mechanical Properties of Metals," *Bulletin No. 146* (February), Am. Inst. Mining and Metallurgical Engrs.; *Transactions*, Vol. 60, p. 474.

(128) 1919 Lukens Steel Company, *Proceedings*, Nat. Elec. Light Association.

(129) 1919 Matsushita, T., "On the Influence of Manganese on the Physical Properties of Carbon Steels," *Science Reports*, Tohoku Imperial University, Vol. 8, p. 79.

(130) 1919 Rosenhain, Walter, and Archbutt, S. L., "On the Inter-Crystalline Fracture of Metals under Prolonged Application of Stress," *Proceedings*, Royal Society of London, Series A, Vol. 96, p. 55.

(131) 1919 Schwartz, H. A., "Some Physical Constants of American Malleable Iron," *Proceedings*, Am. Soc. Testing Mats., Vol. XIX, Part II, p. 248 (1919).

(132) 1920 French, H. J., "Tensile Properties of Boiler Plate at Elevated Temperatures," *Mining and Metallurgy*, No. 158, Section 15, February.

(133) 1920 Gabriel, G., "Comparative Values of Motor Valve Steels," *Iron Age*, Vol. 106, p. 1465.

(134) 1920 Greenwood, J. N., "Hot Flow of Steel during Ordinary Processes of Manufacture," *Iron and Coal Trades Review*, Vol. 100, p. 415.

(135) 1920 Guillaume, C. E., "The Action of Metallurgical Additions on the Dilatation of Nickel Steels," *Comptes Rendus*, Vol. 170, p. 1433.

(136) 1920 Guillaume, C. E., "Values of the Dilatation of Steels of the Nickel Type," *Comptes Rendus*, Vol. 170, p. 1554.

(137) 1920 Hatfield, W. H., and Duncan, H. M., "Turbine Steels—A Research into Their Mechanical Properties," *Transactions*, Northeast Coast Inst. Engrs. and Shipbuilders, Vol. 36, Part 6, p. 321.

(138) 1920 Jeffries, Zay, "Physical Changes in Iron and Steel below the Thermal Critical Range," *Mining and Metallurgy*, No. 158, Section 20.

(139) 1920 Jenkin, C. F., Report on Materials of Construction used in Aircraft, H. M. Stationery Office.

REFERENCE NUMBER	YEAR	
(140)	1920	Lasche, O., "Konstruktion und Materialien im Bau von Dampfturbinen und Turbodynamos," Berlin.
(141)	1920	Lea, F. C., "The Effect of Temperature on Some of the Properties of Materials," *Engineering*, Vol. 110, pp. 293–298.
(142)	1920	Lea, F. C., "The Effect of Temperature on Some of the Properties of Metal," *Proceedings*, Inst. Civil Engrs. (British), Vol. 209, pp. 394–412.
(143)	1920	Mathews, J. A., "The Coefficient of Expansion of Alloy Steels," *Bulletin No. 158* (February), Am. Inst. Mining and Metallurgical Engrs.
(144)	1920	McNiff, G. P., "Strength of Steel at High Temperatures," *Chemical and Metallurgical Engineering*, Vol. 22, No. 14, p. 660.
(145)	1920	Okochi, M., and Sato, N., "On the Growth of Gray Cast Iron," *Journal*, Tokyo University, College of Engineering, Vol. 10, p. 53.
(146)	1920	Sykes, W. P., "Effect of Temperature, Deformation, Grain Size, and Rate of Loading on Mechanical Properties of Metals," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. 64, p. 780.
(147)	1920	White, A. E., "Properties of Iron and Steel at High Temperatures," *Journal*, Am. Soc. Steel Treating, Vol. 2, No. 10, p. 521 (September).
(148)	1921	d'Arcambal, A. H., "Physical Tests on High-Speed Steels," *Transactions*, Am. Soc. Steel Treating, Vol. 2, No. 7, p. 586.
(149)	1921	Doernickel and Trockels, "Die Staucharbeit bei Messing verschiedener Zusammensetzungen in Abhängigkeit von der Temperatur," *Zeitschrift für Metallkunde*, Vol. 13, p. 305.
(150)	1921	Dupuy, E. L., "An Experimental Investigation of the Mechanical Properties of Steels at High Temperatures," *Journal*, Iron and Steel Inst., Vol. 104, p. 91; *Engineering*, Vol. 112, p. 391.
(151)	1921	Edwards and Herbert, "Plastic Deformation of Some Copper Alloys at Elevated Temperatures," *Journal*, Inst. of Metals, Vol. 25, p. 175.
(152)	1921	Freeman, J. R., and Woodward, R. W., "Some Properties of White Metal Bearing Alloys at Elevated Temperatures," U. S. Bureau of Standards *Technologic Paper No. 188*.
(153)	1921	French, H. J., "Tensile Properties of Some Structural Alloy Steels at High Temperatures," U. S. Bureau of Standards *Technologic Paper No. 205*.
(154)	1921	Iokibe, K., and Sakai, S., "The Effect of Temperature on the Modulus of Rigidity and Viscosity of Solid Metals," *Science Reports*, Tohoku Imperial University, Vol. 10, p. 1.

REFERENCE NUMBER	YEAR	
(155)	1921	Johnson, C. M., "Non-Magnetic Properties and Microstructure of Heat-Treated Flame, Acid and Rust-Resisting Steel," *Transactions*, Am. Soc. Steel Treating, Vol. 1, p. 554.
(156)	1921	Korber, F., and Dreyer, A., "Über Blaubrüchigkeit und Altern des Eisens," *Mitteilungen* aus dem Kaiser Wilhelm Inst. für Eisenforschung, Vol. 2, p. 59.
(157)	1921	Maurer, E., and Hohage, R., "Über die Wärmebehandlung der Spezialstähle im Allgemeinen und der Chromstähle im Besonderen," *Mitteilungen* aus dem Kaiser Wilhelm Inst. für Eisenforschung, Vol. 2, p. 91.
(158)	1921	MacPherran, R. S., "Comparative Tests of Steels at High Temperatures," *Proceedings*, Am. Soc. Testing Mats., Vol. 21, p. 852 (1921).
(159)	1921	Rankin, K., "Observations on Stack Corrosion," *Power Plant Engineering*, Vol. 25, p. 677.
(160)	1921	Rittershausen, F., "Stähle für die Chemische Industrie," *Zeitschrift für Angewandte Chemie*, Vol. 34, pp. 413, 444.
(161)	1921	Rosenhain, Archbutt and Hanson, Eleventh Report to Alloys Research Committee, Inst. Mechanical Engrs. (British).
(162)	1921	Spooner, A. P., Discussion of paper by MacPherran, referred to above, *Proceedings*, Am. Soc. Testing Mats., Vol. 21, p. 863 (1921).
(163)	1921	Sykes, W. P., "Effect of Temperature, Deformation, Grain Size and Rate of Loading on Mechanical Properties of Metals," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. 64, p. 780.
(164)	1921	Welter, G., "Elastizität und Festigkeit von Spezialstählen bei Hohen Temperaturen," *Forschungsarbeiten aus dem Gebiete des Ingenieurwesens*, No. 230.
(165)	1921	Westgren, Arne, "Röntgen Spectrographic Investigation of Iron and Steel," *Journal*, Iron and Steel Inst. (British), Vol. 103, p. 303.
(166)		(Reference number not used.)
(167)	1921	"The Failure of Metals under Internal and Prolonged Stress" (Topical discussion by various authors), published by Faraday Society, London.
(168)	1921–1922	International Nickel Company, "Physical Properties of Monel Metal."
(169)	1922	Batson and Hyde, "Mechanical Testing."
(170)	1922	Chevenard, P., "Alliages de Nickel Conservent leur Rigidité dans un Domaine Étendu de Température," *Comptes Rendus*, Vol. 175, p. 486.
(171)	1922	Dews, H. C., "The Use of Non-Ferrous Alloys under Superheat," *Engineering*, Vol. 114, pp. 541–542.
(172)	1922	Dickenson, J. H. S., "Some Experiments on Flow of Steels at Red Heat with a Note on Scaling of Heated Steels," *Journal*, Iron and Steel Inst., Vol. 106, p. 103.

REFERENCE NUMBER	YEAR	
(173)	1922	Dickenson, J. H. S., "The Flow of Steels at a Red Heat," *Engineering*, Vol. 114, pp. 326, 378.
(174)	1922	Edert, H., "Wärmversuche mit Sonderstählen," *Stahl und Eisen*, Vol. 42, p. 961.
(175)	1922	Edwards, C. A., "The Time Factor in Metallurgy," *Metal Industry* (London), Vol. 20, pp. 128–130, 152–153.
(176)	1922	Fowler, Henry, "The Effect of Superheated Steam on Non-Ferrous Metals used in Locomotives," *Journal*, Inst. of Metals, Vol. 28, p. 137.
(177)	1922	French, H. J., "Boiler Plate after Cold-Work or Work at Blue Heat," *Chemical and Metallurgical Engineering*, Vol. 27, p. 211.
(178)	1922	French, H. J., "Effect of Rate of Loading on Tensile Properties of Boiler Plate," *Chemical and Metallurgical Engineering*, Vol. 27, p. 309.
(179)	1922	French, H. J., "Effect of Temperature, Deformation, and Rate of Loading on the Tensile Properties of Low-Carbon Steel below the Thermal Critical Range," U. S. Bureau of Standards *Technologic Paper No. 219*.
(180)	1922	French, H. J., "Stainless Steel at High Temperatures," *Iron Age*, Vol. 110, p. 404.
(181)	1922	French, H. J., "Strength and Elasticity of Boiler Plate at Elevated Temperatures," *Chemical and Metallurgical Engineering*, Vol. 26, p. 1207.
(182)	1922	Friend, J. N., "The Corrosion of Iron," *Carnegie Scholarship Memoirs* (Iron and Steel Inst.), Vol. 11.
(183)	1922	Harper, J. F., and MacPherran R. S., "Tensile Tests of Cast Iron at Various Temperatures," *Iron Age*, Vol. 110, p. 793.
(184)	1922	Jeffries, Zay, "Physical Changes in Iron and Steel below the Thermal Critical Range," Am. Inst. Mining and Metallurgical Engrs., Vol. 67, p. 56.
(185)	1922	Kikuta, T., "The Growth of Gray Cast Iron during Repeated Heatings and Coolings," *Science Reports*, Tohoku Imperial University, Vol. 11, p. 1.
(186)	1922	Langenberg, F. C., Discussion of paper by Jeffries, referred to above, *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. 67, p. 72.
(187)	1922	Lea, F. C., "The Effect of Temperature on Some of the Properties of Metals," *Engineering*, Vol. 113, p. 829.
(188)	1922	Malcolm, V. T., "Steels at Elevated Temperatures," *Bulletin*, The Chapman Valve Manufacturing Co.
(189)	1922	Malcolm, V. T., *Transactions*, Am. Soc. Mechanical Engrs. Vol. 44, p. 1174.
(190)	1922	Orrok, G. A., and Morrison, W. S., "The Commercial Economy of High Pressure and High Superheat in the Central Station," *Transactions*, Am. Soc. Mechanical Engrs., Vol. 44, p. 1119.

REFERENCE NUMBER	YEAR	
(191)	1922	Pilling, N. B., and Bedworth, R. E., "Mechanism of Metallic Oxidation at High Temperatures," *Chemical and Metallurgical Engineering*, Vol. 27, p. 72.
(192)	1922	del Regno, *Rendiconti* della Reale Academia dei Lincei, Roma, (5) 31 (2) 105–107; (5) 31 (1) 464–467.
(193)	1922	Souder, W. H., and Hidnert, P., "Thermal Expansion of a Few Steels," U. S. Bureau of Standards *Scientific Paper No. 433.*
(194)	1922	Souder, W. H., and Hidnert, P., "Thermal Expansion of Nickel, Monel Metal, Stellite, Stainless Steel, and Aluminum," U. S. Bureau of Standards *Scientific Paper No. 426.*
(195)	1923	Bushnell, F. N., "Higher Steam Pressures and Improvement in Station Economy," *Proceedings*, Nat. Elec. Light Assoc., Vol. 80, p. 522.
(196)	1923	French, H. J., and Tucker, W. A., "Strength of Steels at High Temperatures," *Iron Age*, Vol. 112, pp. 193, 275.
(197)	1923	Graziani, F., "Influenza della Temperatura Sulle Proprietà Mecchaniche della Ghisa," *Giornale*, Chim. Ind. Applicata, Vol. 4, p. 53.
(198)	1923	Ito, K., "The Hardness of Metals as Affected by Temperature," *Science Reports*, Tohoku Imperial University, Vol. 12, No. 2, p. 137.
(199)	1923	Jasper, T. M., "The Value of the Energy Relation in the Testing of Ferrous Metals at Varying Ranges of Stress and at Intermediate and High Temperatures," *Philosophical Magazine*, Sixth Series, Vol. 46, p. 609.
(200)	1923	Langenberg, F. C., "An Investigation of the Behavior of Certain Steels under Impact at Different Temperatures," *Carnegie Scholarship Memoirs* (Iron and Steel Inst.), Vol. 12, p. 75.
(201)	1923	Langenberg, F. C., "Investigation of the Influence of Temperature on the Charpy Impact Value of a Group of Steels of Varying Composition," *Year Book*, Am. Iron and Steel Inst., p. 349.
(202)	1923	Lea, F. C., "Tensile Tests of Materials at High Temperatures," *Engineer*, Vol. 135, p. 182.
(203)	1923	Malcolm, V. T., "The Metallurgy of the High-Pressure Steel Valve," *Bulletin*, The Chapman Valve Manufacturing Co.
(204)	1923	Oertel, W., "Festigkeitseigenschaften von Eisen und Stahl in der Kälte and Wärme," *Stahl und Eisen*, Vol. 45, p. 1395.
(205)	1923	Pilling, N. B., and Bedworth, R. E., "Oxidation of Metals at High Temperatures," *Journal*, Inst. of Metals, Vol. 29. p. 529.
(206)	1923	Priester, G. C., and Harder, O. E., "Effect of Temperature on the Mechanical and Microscopic Properties of Steel," *Chemical and Metallurgical Engineering*, Vol. 28, p. 111.

Reference Number	Year	
(207)	1923	Van Patten, N., Bibliography of the Corrosion of Metals and Its Prevention, published by the author, Marblehead, Mass.
(208)	1924	Carrington, H., "The Strength Properties of Wrought Iron, Mild Steel and Nickel Steel at High Temperatures," *Engineering*, Vol. 117, p. 69.
(209)	1924	Germer and Woods, "The Effect of Strain beyond the Yield Point on the Tensile Strength of Soft Steel at Elevated Temperatures," Thesis, Massachusetts Inst. Technology.
(210)	1924	Goerens, P., "Die Kesselbaustoffe," *Zeitschrift*, Verein deutscher Ingenieure, p. 41, January 19.
(211)	1924	Lawrence, John H., "A Résumé of Recent Power-Station Developments," *Mechanical Engineering*, Vol. 46, No. 3, p. 144.
(212)	1924	Malcolm, V. T., "Physical Properties of Metals at Elevated Temperatures," *Transactions*, Am. Soc. Steel Treating, Vol. 5, No. 3, p. 256.
(213)	1924	Moore, H. F., Private Communication, University of Illinois.
(214)	1924	Sauveur, A., "What is Steel?" Paper presented before annual meeting of Am. Inst. Mining and Metallurgical Engrs., February; *Iron Age*, Vol. 113, p. 581.
(215)	1924	Speller, F. N., "Tensile Properties of Various Metals at Elevated Temperatures," National Tube Co.
(216)	1924	"An Investigation into the Effect of High Temperatures upon Metals," *Circular No. 163*, Crane Co. (Chicago).

INDEX TO BIBLIOGRAPHY[1]

Index to Bibliography Covering Ferrous Metals

(Includes the majority of references subsequent to 1914 and a few earlier ones.)

Type of Test	Cast Iron	Malleable Iron and Semi-steel	Cast Steels	Mechanically Worked Metals		High Alloy Content Steels and Heat Resisting Alloys
				Wrought Iron and Carbon Steels	Ordinary Structural Alloy Steels	
Tension	119 183 147 197	131 216 147	147 212 150 216	109 147 164 196 113 150 172 204 116 153 177 206 119 155 178 208 125 156 179 214 127 158 181 132 160 187 144 162 190	123 162 196 133 164 204 153 170 208 157 172 210 158 174 212 160 179	109 158 172 123 160 180 127 162 196 133 163 204 148 164 216 157 170
Torsion				214 216		216
Hardness	198			53 63 156 62 71 198	63 71 133	71 123 133
Crushing	71		71	71	71	71
Impact				113 156 200 125 160 201	160 201 200 210	123 160 201
"Flow" Tests				172	124 172	170 172
Expansion	193	131		117 193	117 143 193	117 193 126 194
Intercrystallin Deterioration	111 185 145			118 137 167 127 138	137 172	172
Oxidation (includes mainly scaling tests)	182			123 182 172 205	123 133 172	115 133 205 123 172
Special References or Descriptive Reports	145			105 129 154 167 110 134 155 199 114 137 159	110 140 199 137 167	126 136 135 154

Index to Bibliography Covering Non-Ferrous Metals

(Includes the majority of references subsequent to 1910 and a few earlier ones.)

Type of Test	Copper	Brasses	Bronzes	Cupro-nickel	Nickel and Nickel Alloys	Aluminum and Aluminum Alloys	Bearing Metals	Miscellaneous
Tension	64 127 79 141 82 142 85 154 96 171 102 187 107	64 141 82 142 83 171 85 187 102 216 107	57 141 64 142 73 171 79 187 83 190 85 212 98 216 122	79 141 82 142 85 171	106 190 142 192 146 212 154 216 170	82 154 85 161 146 187		100 146 127 154
Torsion	108	108	108	108	108			108 154
Hardness	112 151 120 175	120 175 141	120 175 141	120 151 141 175	112 141	112 151 120 161 141 175	152	112 151 120 175
Crushing	149	149						
Impact	120 175	120 175	57 73	120 175		120 175 161		
"Flow" Test	151			151		151		151
Miscellaneous			176					

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[1] The numbers given are those of the papers in the Bibliography and include any discussions of the original reports.

DISCUSSION

Mr. Wilhelm. MR. R. B. WILHELM[1] (*presented in written form*).—This discussion deals with the tensile properties of medium-carbon steel at temperatures between 20 and 500° C. A description of the apparatus used for these tests is given, together with certain numerical data obtained. The discussion describes only the beginning of an investigation planned by the Westinghouse Electric and Manufacturing Co., the main points of which will be to investigate the properties of certain materials under prescribed conditions. The effect of time at high temperatures is also included in the program. From the results of the investigations so far published on this subject, the behavior of the material either under normal test conditions or under a long-time effect are separately considered. It is felt that some valuable results from both methods of testing can be obtained if these tests are made on the same materials. Such is the object in view, of which the results given are preliminary.

In the normal tension test, special care was taken to determine the modulus of elasticity and proportional limit. From the modulus of elasticity given in the paper, it is possible to obtain some data on the value of the modulus of rigidity at different temperatures by considering the values for Poisson's ratio for different temperatures as found and published by H. Carrington.[2]

Since it is our opinion that a difference in one of the constituent elements of the steel may materially affect the properties at high temperatures, the complete chemical analysis is given of the material tested. This may possibly help to clear up the seemingly contradictory results found by different investigators. We note, for instance, that for carbon steels of similar carbon content the values of proportional limit and yield point show an increase in some cases and a decrease in others, with increase of testing temperature. Further tests may decide to what extent either the composition or the state of the material is responsible for this fact.

For the first series of tests a carbon steel was chosen in order to form a basis on which the results found for alloy steels may in the future be compared.

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[1] Research Department, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

[2] *Engineering*, 1924, No. 3029.

APPARATUS USED FOR HIGH-TEMPERATURE TESTS

Mr. Wilhelm.

Testing Machine—All the tests were carried out on the latest type of hydraulic 100,000-lb. tension testing machine supplied by the Alfred J. Amsler Co., Schaffhouse, Switzerland. The machine is equipped with an attachment for taking autographic diagrams.

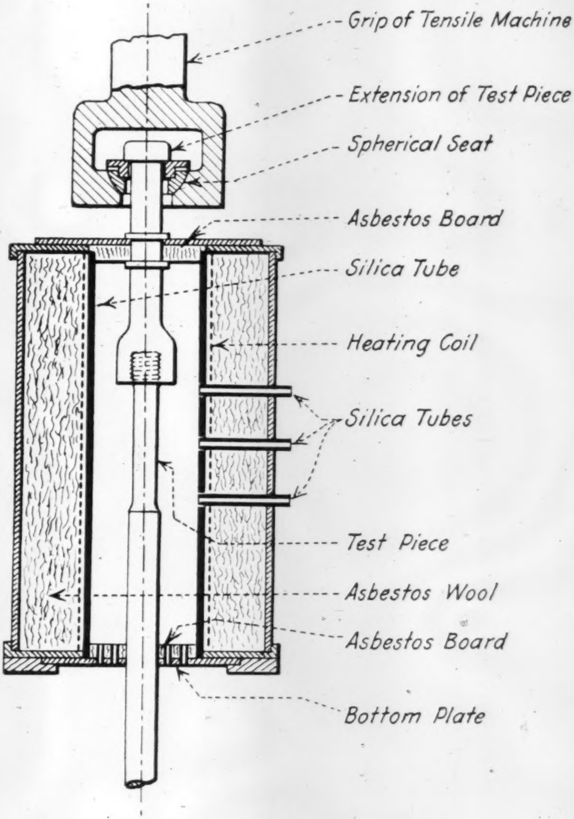
Grip of Tensile Machine
Extension of Test Piece
Spherical Seat
Asbestos Board
Silica Tube
Heating Coil
Silica Tubes
Test Piece
Asbestos Wool
Asbestos Board
Bottom Plate

FIG. 1.—Electric Furnace for Tension Tests.

(Coil wound from $\frac{1}{8}$ by 0.032-in. nichrome wire; resistance, 125 ohms per 1000 ft.)

Shortly before executing these tests the machine was checked up by means of a standardizing box, supplied by the builder of the machine. The errors in the readings of the load applied by the machine proved to be within ±0.5 per cent.

Furnace and Temperature Measurements.—According to tests carried through by Welter,[1] for temperatures up to 500° C. and for

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[1] Forschungsarbeiten aus dem Gebiete des Ingenieurwesens, Heft 230, p. 11.

Mr. Wilhelm. the duration of the tests, no scaling occurs on medium-carbon steel which might otherwise affect the results. As a rule alloy steels show a greater resistance against scaling than plain carbon steels. Considering these facts, it was decided to use an air-bath furnace instead of a liquid. In many respects an air-bath furnace offers advantages over the liquid-bath furnace. In the first case the extensometer with the mirrors can be inserted from the bottom, and the mirror carriers and the mirrors are thus subjected to much less heating. Besides, an air-bath furnace is easier to handle before and after the test.

A section through the electrically heated furnace is given in Fig. 1. The furnace consists essentially of a silica tube, 2½ in. in inside diameter, 3 in. in outside diameter and 9 in. in length, the heating coil, an outer brass tube, 6 in. in outside diameter, top and bottom plates, and the necessary asbestos board and wool for heat insulation. The length of the furnace was limited by the dimensions of the machine. By means of the top plate the furnace is suspended from the test specimen. Sliding bottom plates are provided to remove the high-temperature extensometer during the test after having passed the proportional limit. The small silica tubes are inserted horizontally to take care of the thermocouples. Fig. 2 shows the coil unequally spaced to compensate for cooling at the ends. In addition

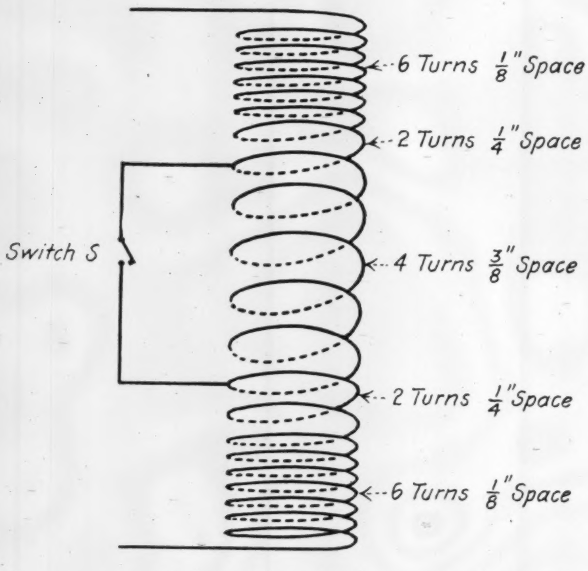

FIG. 2.—Coil Unequally Spaced to Compensate for Cooling.

to this, several turns in the center can be put in parallel with a line of low resistance by closing switch S. In further development, switch S may be replaced by a resistance which would permit regulation of the amount of current going through each of these branches. **Mr. Wilhelm.**

The thermocouple readings in the center of the furnace and at 2 in. distance toward top and bottom are given in the following table for three different ranges of temperatures:

Location of Thermocouple	Temperature, deg. Cent.		
	200	300	500
Top	200	296	499
Center	197	300	502
Bottom	206	308	505

Comparison tests of thermocouples welded on, and others pushed against, the test specimen gave at the desired temperatures a difference of 12 to 25° C., the couple welded on the test specimen showing the lower temperature.

The test specimen being exactly in the middle of the furnace and the gage length with the fillets being 4 in. long, the thermocouples of the top and the bottom at 4 in. distance will coincide with the increased section of the test specimen, where due to conductivity a decrease in temperature was noticed. Therefore the top and bottom thermocouples proved to be more valuable in indicating the fluctuations of temperature rather than giving any absolute value, which exclusively was determined by the pyrometer in the middle of the gage length.

The materials used for the thermocouples were copper and advance. For taking the readings they were pushed slightly against the test piece. A potentiometer in conjunction with a calibration curve for the above mentioned metals was used for determining the temperature.

High-Temperature Extensometer.—The telescopes and the mirrors of the Martens mirror apparatus were used in the ordinary way for measuring strains. The comparison strips had to be subjected to a change in order to transmit the extension of the gage length outside of the furnace. This has been done on the same principle as in tests executed by other investigators and is shown schematically in Fig. 3.

Two rings with knife edges inside and V-notches outside secure the position of the comparison strips. Spring attachments hold the strips in their position. The mirror carriers rest in a V-notch on one strip and on a cylindrical surface on the other. In the design special care was taken that no part of the instrument was supported in more than three points to secure its position. Any extension between the

Mr. Wilhelm. points *A* and *B* will produce a displacement of the points *C* and therefore affect the position of the mirrors, and, in consequence, the reading on the scale through the telescope. With regard to the accuracy of the readings, the distance *AB* on the test specimen ought to be as long as possible; on the other hand, the difficulty of having a uniform temperature over a great length had to be taken into consideration. A length of 2.75 or 3 in. seems to comply best with both requirements.

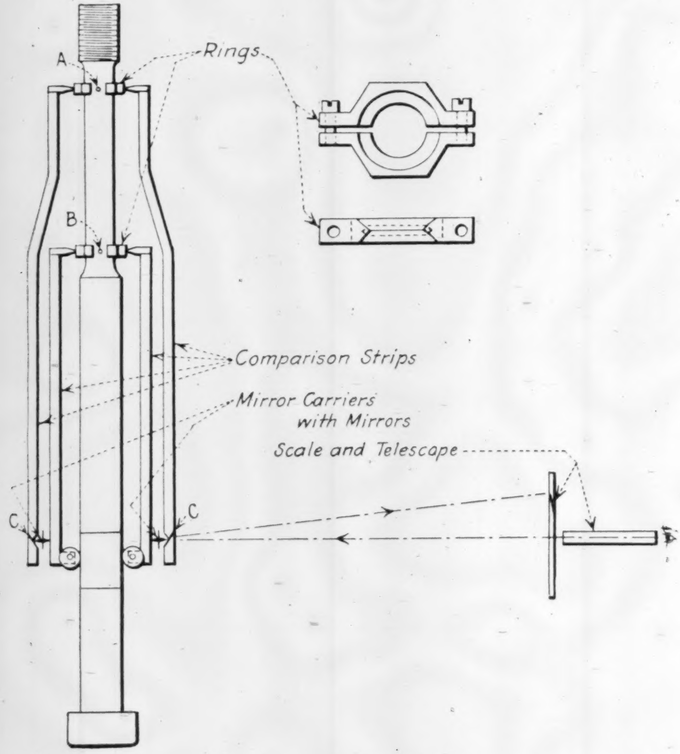

FIG. 3.—High-Temperature Extensometer.

The material used for the instrument had to show the following characteristics:

(*a*) Machineability;

(*b*) No scaling at high temperatures;

(*c*) Good tensile properties at high temperatures.

Stainless steel was considered suitable for the temperatures in question.

The instrument was compared with the normal-temperature Martens equipment and the difference found to be less than one per cent.

TENSION TEST SPECIMENS

Mr. Wilhelm

The test specimens were machined from 2-in. diameter steel bars in pairs. In further tests a smaller diameter may be used in order to avoid the milling of the bars in the longitudinal direction. Fig. 4 shows a test specimen with the extension grip and the high-temperature extensometer mounted on it. The cylindrical part of the test specimen subjected to the test has a diameter of 0.505 in. and a length of 3 in., which are used for the extensometer measurements.

In order to determine the elongation, the whole length was divided in parts 0.25 in. long and a fine mark made with a center point. The fact that most of the test specimens broke between two marks and not in the marks may prove that there is no considerable influence on ultimate strength due to this dividing method. The value of elongation was determined for a standard gage length of 2 in. as well as for 3 in. and fracture was supposed to be in the middle. With the intention to save material and machining costs, further tests with grips on both ends of the test specimen will be made.

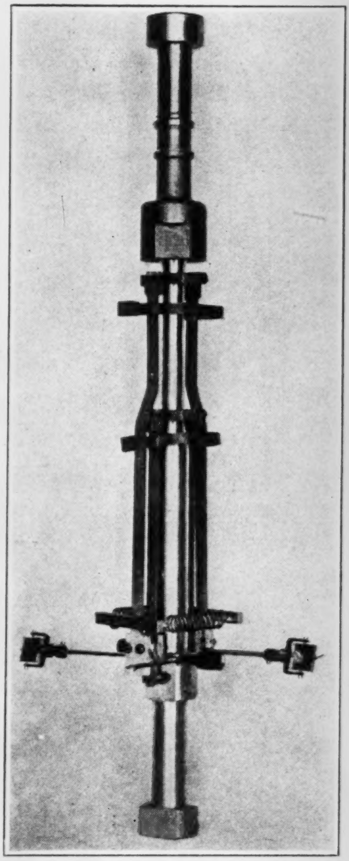

FIG. 4.—Test Piece with Extension Grip and High-Temperature Extensometer.

EXECUTION OF TESTS

After checking the main dimensions and dividing the gage length, the extensometer was assembled without the mirror carriers. The test specimen and instrument were inserted in the furnace and all together put into the tension testing machine. After putting the mirror carriers in place and adjusting the mirrors, a test was made at normal temperature and at a low stress (within the proportional limit) to insure that the extensometer and mirrors were set correctly. Heating

Mr. Wilhelm. of the furnace was then commenced, and after it reached the desired temperature, it was kept for at least two hours before the test specimen was put under load. Most of this time was necessary for an accurate adjustment of the electric current to maintain a state of equilibrium in temperature, the latter being indicated by thermocouple as well as by extensometer readings, provided that there was no, or at least no variable, stress on the test specimen. Then a gradually increasing load was applied and extensometer readings were taken at equal intervals. After passing the yield point, or after an equivalent increase in strain at temperatures without an accentuated yield point, the mirrors were removed. In order to avoid any disturbance of the constant temperature the comparison strips were removed only after passing the ultimate strength and previous to fracture.

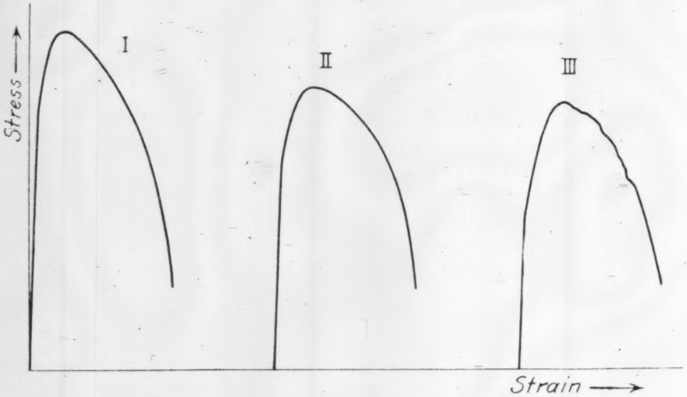

Fig. 5.—Speed Effect at 500° C., Medium-Carbon Steel.

Test number	I	II	III
Duration of test, min	6	70	240
Ultimate strength, lb. per sq. in	53 500	44 500	41 600

Preliminary Tests on Medium-Carbon Steel

A series of tests was first carried out at various temperatures without the high-temperature extensometer. This showed an increasing effect of testing speed especially upon the ultimate strength. Fig. 5 shows the diagrams taken at 500° C. with different speeds, the durations of the whole test being 6, 70 and over 240 minutes, respectively.

Mr. Wilhelm.

A second series was carried out with the high-temperature instrument. Two speeds were chosen, one which just allowed readings being made and the other which was a very low one, that is, 1000 and 100 lb. increase of load on the machine per minute, respectively. This test, however, did not show a very distinct speed effect. This fact might have influenced Mr. French of the Bureau of Standards to use a photographic method for recording the stress and strain values at high testing speed.

For our test it was decided to use a normal testing speed and to study the time effect, especially of long time, on a separate apparatus.

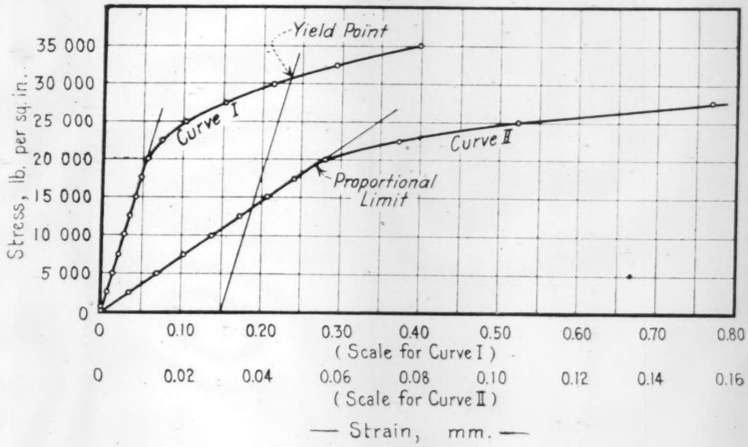

Fig. 6.—Stress-Strain Curve Illustrating Proportional Limit.

(Test piece No. 721–7, medium-carbon steel. Testing temperature, 300° C.; proportional limit, 19,500 lb. per sq. in.; yield point, 30,600 lb. per sq. in.; modulus of elasticity, 27,600,000 lb. per sq. in.)

Another phenomenon worthy of note is the fact that fracture of the test specimen occurred at the point of minimum temperature, provided that the ultimate strength increased with increase of temperature, and at the point of highest temperature if the ultimate strength decreased with increase of temperature.

Properties Determined in Tension Tests

The elastic properties, such as proportional limit and modulus of elasticity, were considered the most important features of the tests. In addition to these the values of yield point, ultimate strength, elongation and reduction of area were determined.

Proportional limit was defined as the stress value at which the stress-strain curve showed a distinct deviation from a straight line.

Mr. Wilhelm. It is necessary to add that the same scale for stress and strain had to be used in these determinations.

Since the yield point was not accentuated at higher temperatures, a certain method of expressing this value was adopted. In these tests, therefore, the yield point is taken as the intersection of the stress-strain curve and a straight line parallel to the line of proportionality and passing through the abscissa at a strain of 0.2 per cent of the gage length. That means that by unloading at this stress value the permanent set would amount to 0.2 per cent of the gage length.

This definition is widely adopted in European laboratories for materials without accentuated yield point. A point determined in such a manner gives valuable information with regard to the shape of the curve beyond the proportional limit. Fig. 6 shows the application of these definitions on a stress-strain curve, taken at a testing temperature of 300° C.

The modulus of elasticity was calculated from the formula:

$$E = \frac{\Delta P \cdot l}{s \cdot \Delta \lambda}$$

where ΔP = increase in load in pounds from reading to reading;
l = distance A-B in inches (Fig. 3);
s = section of test piece in square inches;
$\Delta\lambda$ = average increase in extension, from reading to reading up to proportional limit in inches.

The other values are determined in the usual manner and need no further explanation.

CHARACTERISTICS OF MATERIAL TESTED AND RESULTS OBTAINED

Chemical Analysis.—The material used for these tests was taken from the same heat and all the bars analyzed. The values obtained varied within the limits given below:

Carbon	0.37 to 0.40	per cent
Manganese	0.63 to 0.69	"
Silicon	0.11 to 0.14	"
Phosphorus	approximately 0.012	"
Sulfur	approximately 0.037	"

Phosphorus and sulfur were only determined from some of the bars.

Treatment of Material.—Before machining, the material (2 in. in diameter) was normalized at 875° C., soaked three hours at temperature, and air-cooled.

DISCUSSION OF THE RESULTS

Mr. Wilhelm.

From Fig. 7 the decrease in slope of the stress-strain curve with increasing temperature will be seen. As this slope determines the modulus of elasticity, it may be noted that there is only a slight decrease at the beginning and a more accentuated one at higher temperatures. Fig. 8 gives the reproduced autographic diagrams. The suppression of the yield point at temperatures higher than 260° C.

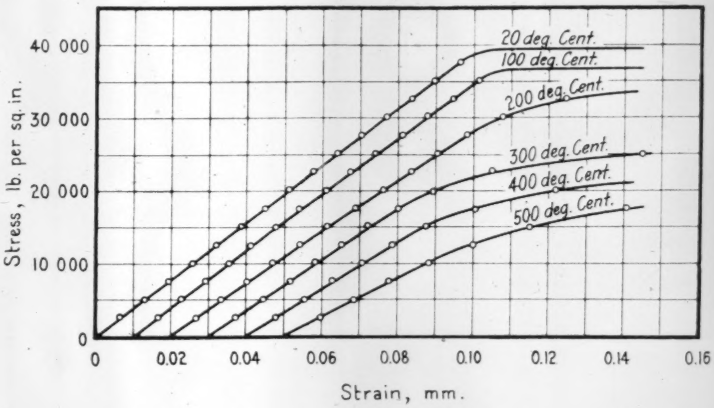

FIG. 7.—Stress-Strain Curves at Various Temperatures, Medium-Carbon Steel.

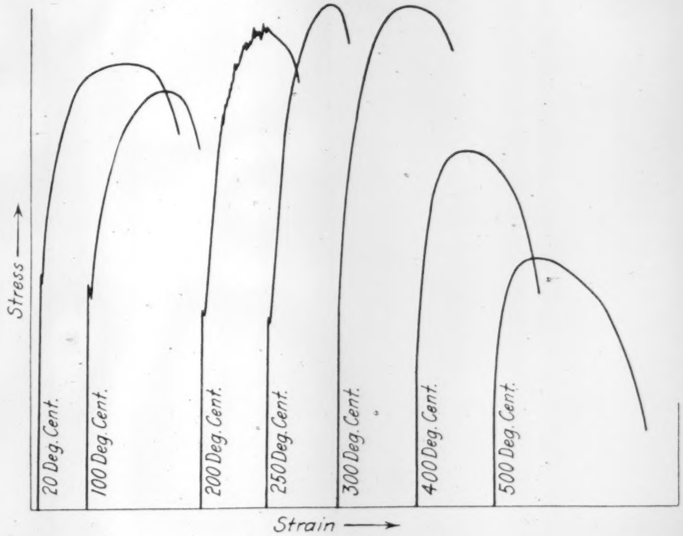

FIG. 8.—Autographic Diagrams for Various Temperatures, Medium-Carbon Steel.

Mr. Wilhelm. is clearly shown. Furthermore, it is interesting to note that the diagram taken at 200° C. shows accentuated vibrations before reaching the ultimate stress. The same phenomenon was observed by Portevin and Le Chatelier.[1] These vibrations may partly be due to the pendulum of the testing machine, but it appears logical to state that a primary cause has to be sought in a change of the material itself.

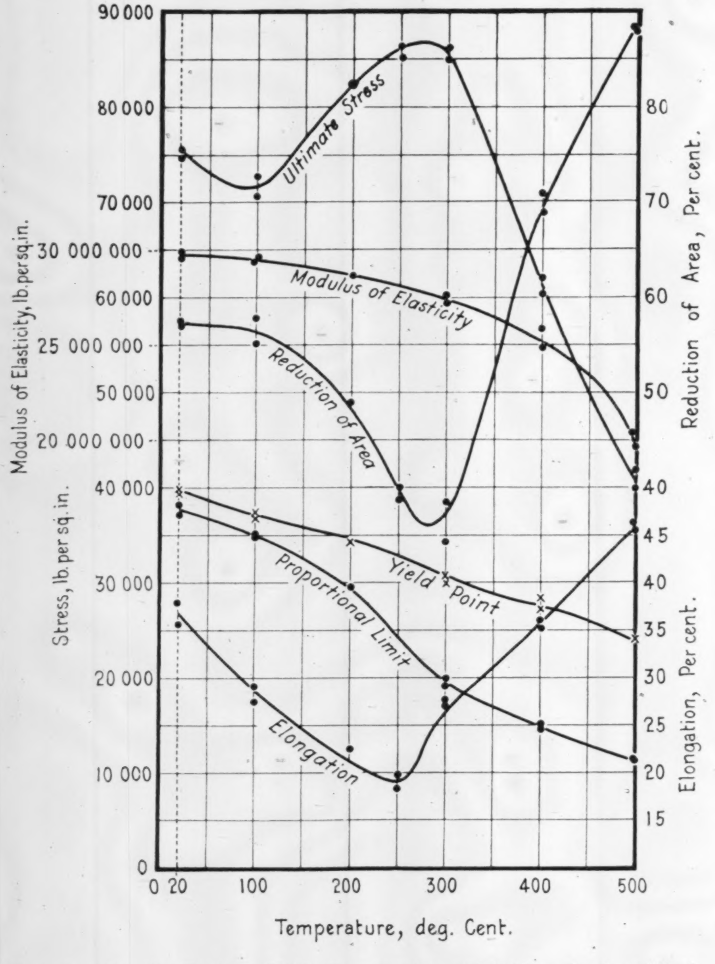

FIG. 9.—Tensile Tests at High Temperatures, Medium-Carbon Steel.

Fig. 9 gives the complete results of the tension tests. It will be observed that the curves of the proportional limit and yield point

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[1] *Comptes Rendus*, Vol. 176, p. 507.

Mr. Wilhelm.

show from the beginning a decrease in stress with increase of temperature. The ultimate strength shows a minimum at about 100° C., but attains a maximum at about 260° C., from where it falls sharply, up to the highest testing temperature. The curves for elongation (on 2-in. gage length) and reduction of area are of similar character, but it may be noted that the minimum elongation is reached at a somewhat lower temperature than that of reduction of area.

The change in the modulus of elasticity expressed by the ratio E_t/E_{20} in which E_t = modulus at temperature t° C., and E_{20} = modulus at temperature 20° C., is given below:

	TEMPERATURE, DEG. CENT.					
	20	100	200	300	400	500
E_t/E_{20}..............	1	0.987	0.961	0.920	0.853	0.657

On this occasion the writer wishes to express his indebtedness to Messrs. J. M. Lessells and S. Timoshenko for their valuable suggestions concerning these tests and to the Westinghouse Electric and Manufacturing Co. for the permission to publish these results.

Mr. Lester.

MR. H. H. LESTER[1] (*presented in written form*).—Mr. Malcolm's reference to X-ray testing touches a field so new that no one can predict now the influence this method will have on production methods. Mr. Westgren in Sweden pioneered in the field of applying X-ray analysis to the structure of steel at high temperatures. Mr. Malcolm referred to the original article by Mr. Westgren. Since this was published he has continued this work and there was presented at the May, 1924, meeting of the British Iron and Steel Institute a further contribution along the same line. In this paper the previous results with regard to δ iron are confirmed. That is, there is a fourth critical point in the steel constitution diagram. Apparently molten steel in freezing changes to cubic crystals of the body-centered type. At around 1450° C. the body-centered cubes change to the face-centered cubic crystals characteristic of austenite. At around 760° C. the face-centered type changes to the body-centered type characteristic of α iron, the iron usually found at room temperature in ordinary steels. With regard to carbon in steel at high temperature, Westgren shows that the face-centered crystals of austenite are enlarged due to the presence of carbon. This indicates that the carbon atoms are forced into the interstices between the iron atoms at temperatures where γ iron is formed. Work by Bain, McKeehan, and others has shown that metallic solid solutions are formed by atoms of the solute replacing atoms of the solvent in the crystal structure of the solvent. Westgren's work points out the possibility of another type of solid solution

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[1] Research Engineer, Watertown Arsenal, Watertown, Mass.

Mr. Lester. in which the solute atoms are forced between the solvent atoms without breaking up its structure. According to this, alloy steels may be made up of three types of constituents, that is, mechanical mixtures of different metals and two kinds of solid solutions. In addition, we may have chemical compounds. Chemical analysis may be used to distinguish definite compounds, but nothing we know of except X-ray tests will distinguish between mixtures and the two types of solid solutions.

That a knowledge of solid solutions and mixtures is highly important in steel practice is indicated by the fact that in Watertown Arsenal four different solid solutions were found in a single specimen of high-speed tungsten tool steel. Control of these solutions probably will be effected through heat treatments. It is necessary to correlate the X-ray data with physical tests to determine the value of these solutions. This information is being gradually accumulated in the Watertown laboratories and elsewhere.

When we consider the various changes in structure that iron undergoes in cooling from the liquid state to room temperature, the fact that alloy constituents often tend to delay or prevent these changes, and the fact that different rates of cooling also affect these changes, we would expect to find in castings, particularly in chilled castings, metal that is by no means in a state of equilibrium. It may be full of partially completed physical reactions. These arrested developments are no doubt responsible for many physical peculiarities. Martensite is an example of arrested developments and its hardness is due to arrested physical reactions. X-ray investigation probably will slowly unravel the tangle of cast-metal structures and give us the knowledge to control to our profit these partially completed reactions.

Mr. Holz. MR. HERMAN A. HOLZ[1] (*presented in written form*).—Referring to the paper by Mr. Malcolm on the methods of testing metals at abnormal temperatures in which the periods of stress application must often be extended to hours, days and weeks, it will be of interest to mention here the special apparatus (Fig. 10) recently developed by Mr. Alfred Amsler for the automatic maintenance of a constant load, independent of the deformation of the specimen, in his well-known tension and compression testing machine. This load-maintaining device has been developed especially for research work on the physical properties of metals at elevated temperatures extending over long periods and operates automatically for any desired period, for days or weeks. It thus produces the same effect as the direct hanging of known weights onto a test specimen, as used by Dickenson in his high-temperature researches.

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[1] Testing Engineer, New York City.

Mr. Holz. The Amsler pendulum dynamometer with its self-contained "primary standard" of pressure measurement against which the load in the testing machine is automatically balanced during the entire testing operation is too well known to require a detailed description. The automatic load-maintaining apparatus consists of a very simple and effective electric-contact attachment to the load dial of this dynamometer. The contact is made and broken through the load-indicating pointer. The contact arrangement is connected to a mercury tilting switch and closes or opens the electric circuit. The apparatus actuates, through a solenoid, a device which stops the oil-pressure pump of the testing machine immediately the limit of load allowable is reached, and starts it again as soon as the oil pressure in the testing machine sinks below the lower limit which had been set. A movement of two

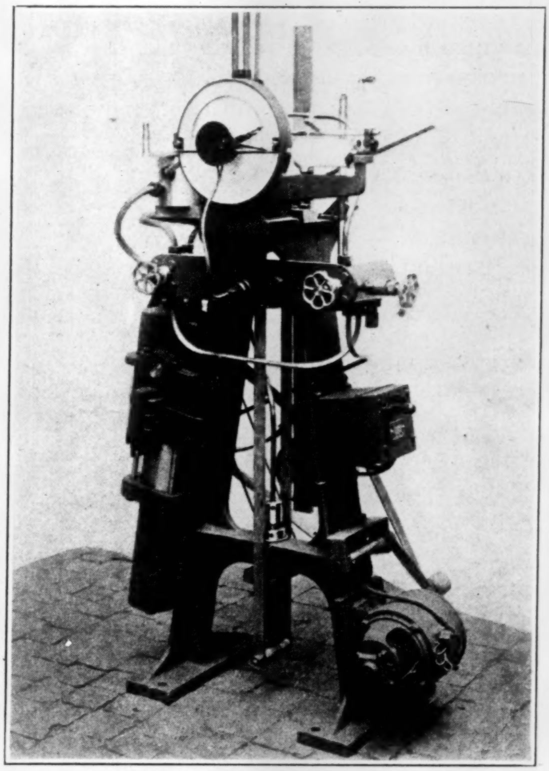

FIG. 10.—Amsler Pendulum Dynamometer with Apparatus for Automatic Load Maintenance, Independent of the Deformation of the Specimen.

Mr. Holz. millimeters covered by the pointer suffices for reversal. To prevent any abrupt action of the mechanism, a regulating valve is fitted in the pressure regulator.

Mr. Malcolm has described some of the difficulties usually encountered in attempting to obtain a uniform temperature over the entire length of a heated test bar. In the design of electric resistance furnaces of this type it may be useful to make the heating element not of one continuous wire spiral, but to use a number of separate wire spirals, arranged along the heating tube, with no electrical connection between the various sections making up the entire heating element. If each of these spirals is controlled separately by means of rheostats, it will be possible to obtain a uniform temperature over the entire length of the test bar. The influence of the cold-specimen heads which conduct a considerable quantity of heat away can thus be offset and eliminated.

There is one method of heating the specimens which Mr. Malcolm has not mentioned. The writer refers to the method of using the tension test specimen itself as resistor in an electric circuit of low voltage and high amperage, by the utilization of alternating current and a suitable transformer. If this method of heating could be successfully applied, it would possess the important advantage that the bars would be heated progressively from the inside toward the outer portions, and not *vice versa*. An arrangement of this kind may also simplify the application of optical extensometers.

Welter, who developed a special gas furnace for his researches, calls attention to the possible influence of magnetic induction, as produced by electric furnaces made from a coil of resistance wire, on the strength and elastic properties of steel specimens. He claims that his gas furnace, constructed in two parts connected by hinges for convenient opening and closing, permits a temperature regulation and maintenance to 0.5° C. at low and high temperatures. This accurate control, due mainly to the design of the furnace, is facilitated by the insertion of a pressure regulator in the gas duct. Although the tendency during recent years has been to apply electricity to the production of high temperatures in the laboratory, Welter points out the disadvantages of the electric furnace for this particular work in testing practice and describes means developed by him for producing and maintaining accurate temperature control by the use of gas which can hardly be improved upon, if at all equalled, by using electric current. If the writer is not mistaken, Welter's furnaces for use in testing machines are now being produced abroad on a commercial scale.

Regarding the methods to be applied in high-temperature researches on metals, there are two methods which we will have to develop for routine tests at high temperatures, while a third one will yield much information of value in research. The writer is referring, first of all, to hardness tests at elevated temperatures, because resistance to indentation under static load and strength of the material run more or less parallel. Unfortunately, the standard static Brinell test is not suitable under these circumstances, mainly for the reason that it does not produce impressions of geometric similarity, so that the results are not independent of the load applied and of the impressions produced. At normal temperatures this is not very serious; we can standardize the load applied and most of the other testing conditions. In working at high temperatures, however, we have to figure with considerable variations in the plastic properties of the materials under investigation, and we therefore cannot use a method which compares the various materials, in entirely different states of deformability, to entirely different degrees of deformation. **Mr. Holz.**

The writer believes that the Ludwik cone test, which does not possess these disadvantages, will be quite suitable for high-temperature tests and that Ludwik's researches on "the variation of internal friction of metals with temperature" can be extended from the nonferrous to the ferrous field. The conical indenting tool as designed by Ludwik could be constructed from a suitable cobalt-chrome alloy. The application of the Ludwik test, in this instance, would certainly be preferable to the use of kinetic hardness tests as recently developed by Edwards in England and by Wuest and Bardenheuer in Germany. He does not believe that the various formulas at which these investigators arrived during their comparative static and kinetic ball-hardness tests at room temperatures will hold good at elevated temperatures. Furthermore, static tests such as Ludwik's will always yield data of greater accuracy and reliability than kinetic tests, because in static tests all forces applied and energy absorbed are under perfect control and measurable with accuracy.

The second routine test which is urgently needed, not only in high- but also in normal-temperature tests, is one permitting the determination of the elastic limit and of the limit of proportionality of metals exposed to impact forces. Mr. Malcolm calls attention to the important fact that it would be quite incorrect to use the tensile strength of metals at high temperatures as a basis of design. The writer believes that it would be still more dangerous, in many cases, to base the design of metal structures exposed to impact on the data of their resistance to fracture by impact. Almost nothing has been

Mr. Holz. done so far in elastic-limit determinations under impact, although it is undoubtedly of the greatest practical importance to study the impact elastic range of materials, at normal and elevated temperatures.

The third method, which the writer previously called a research method and which must be extended to the field of high temperatures, is the so-called "looping" method developed by Dalby. It is one of the most sensitive methods ever devised on the micro-structure of metals and is particularly suitable for investigation of the metals in their plastic state. Dalby's methods and researches are now so well known that it will not be necessary here to go into further details. Looping tests at high temperatures, by the use of the Martens optical extensometer, have been carried out on iron and copper by Mauksch in Germany, and valuable data have been obtained. It would be very desirable to extend these high-temperature looping tests to the alloy steels.

Mr. Marsh. MR. KIRTLAND MARSH.[1]—In order to make the data obtained by several observers comparable, the temperature of the test specimens should be accurately determined, and in some of the apparatus described in Mr. Malcolm's articles it seems improbable that the temperature of the specimens could have been accurately measured with the equipment arranged as shown. The results, given in the Symposium, of tests made by some of the observers show the temperature differences which may have existed in the test specimen and the differences in temperatures as measured by thermocouples mounted in different manners. Data on physical properties at other than room temperatures would be of much greater value if it were definitely known that the reduced section of the specimen was at a uniform temperature throughout, and that the temperatures given were the actual temperatures of the specimen. Therefore, since there may be some doubt as to the uniformity of temperatures throughout a test specimen and also as to the accuracy of the specimen temperatures as measured, every observer, not only for his own benefit but also to accredit the results of his work to others, should carefully determine the temperature gradient throughout the specimen and the accuracy with which the actual temperature of the specimen is measured.

A thermocouple measures the temperature of its hot junction, but if a temperature gradient exists close to the junction it can not be safely assumed that the hot junction is at the same temperature as another object, even closely adjacent to it, whose temperature it is desired to measure. In the case of a furnace where the holders or the specimen itself extend outside of the heating chamber, as is necessary

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[1] Pyrometric Engineer, Aluminum Co. of America, New Kensington, Pa.

Mr. Marsh. for this work, a large amount of heat is conducted out of the furnace through the holders or specimen with the result that the temperature of the specimen easily might be 150° F. or more below the temperature of the medium surrounding it. Under such conditions, a couple with its hot junction held in contact with the specimen would probably indicate a temperature more nearly equal to the temperature of the medium surrounding the specimen than the temperature of the specimen itself, due to conduction of heat along the wires of the thermocouple to the hot junction. This is particularly liable to obtain in the case of a couple, the hot junction of which consists of a weld at the end of a twisted section of the wires, for in such a couple the hot junction would be at the first point of electrical contact between the two thermoelements, which in some cases might be at the beginning of the twist rather than at the welded portion. Even in the case of a couple welded without any twisting of the wires and placed in contact with the specimen there would be such poor thermal contact between the hot junction and the specimen that it is highly probable that more heat would be conducted along the wires to the hot junction than would be conducted from the junction to the specimen so that the junction would be at a higher temperature than the specimen.

The conduction of heat by the specimen or the holders extending outside the furnace cannot be eliminated, but it is perfectly possible to practically eliminate the conduction of heat away from that section of the specimen which it is desired to maintain at a uniform and constant temperature, namely, the reduced section. This can be accomplished if the heat, which ordinarily would be drawn from the reduced section of the specimen and conducted away by the holders or specimen extending beyond the furnace, is otherwise furnished by providing enough heat absorbing surface between the ends of the reduced section of the specimen and the ends of the furnace or by using auxiliary heaters around that part of the holders or specimen which projects beyond the end of the furnace.

If the conduction of heat away from the specimen is eliminated, a practically uniform temperature throughout the specimen can be secured and the temperature of the specimen, after temperature equilibrium in the furnace is reached, will agree more closely with the temperature of the medium adjacent to it. A radiation shield between the heaters and specimen may be found necessary in some cases. Under these conditions the temperature of the specimen can be easily and accurately determined.

To determine if the above conditions exist, a very careful temperature survey should be made and the following general method will

Mr. Marsh. serve this purpose. Locate thermocouples as shown in Fig. 11, the couples at positions 1, 2, 3, 5, 6, 7, and 8 being located with the hot junction on the longitudinal axis of the specimen and inserted as illustrated at (*a*) in the same figure. This latter shows a small-gage thermocouple with laid asbestos insulation and with a butt-welded hot junction. The couple is inserted in a hole, drilled diametrically through the specimen, with the hot junction on the center line of the specimen; a soft rivet driven into a second radial hole perpendicular to the first forces the hot junction firmly against the specimen, thereby making good thermal contact. The asbestos insulation on the wires extends inside the hole and prevents the wires from coming in contact with the specimen and forming another junction and also helps to retard heat

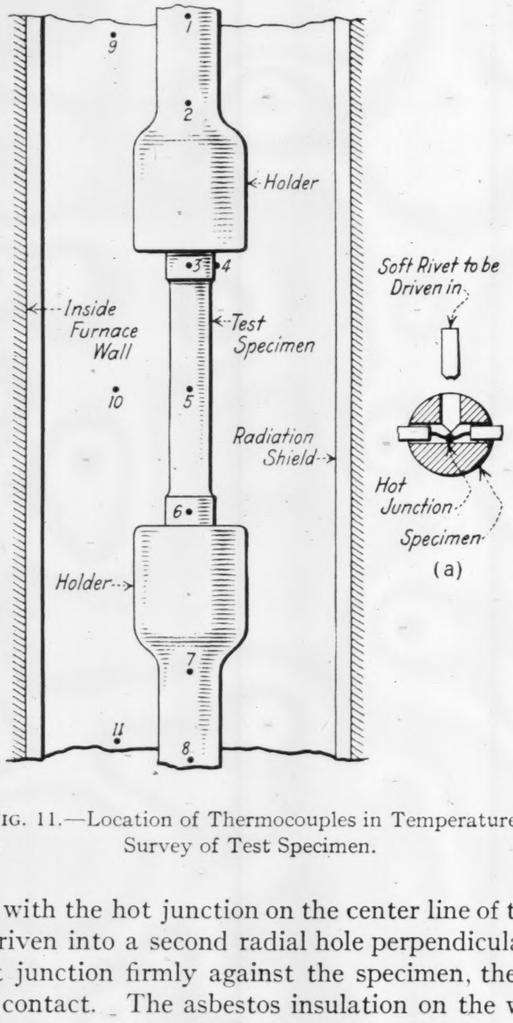
1
9
2
Holder
3
4
Soft Rivet to be Driven in
Inside Furnace Wall
Test Specimen
10
5
Radiation Shield
Hot Junction
6
Specimen
(a)
Holder
7
11
8

FIG. 11.—Location of Thermocouples in Temperature Survey of Test Specimen.

flow between the wires and surrounding atmosphere. This arrangement, it is believed, will measure the temperature at the center of the specimen very accurately. **Mr. Marsh.**

Couple No. 4 is held against the specimen by as small a band as possible; the hot junction of this couple should be in the form of a bead flattened out a little with a hammer to provide greater contact surface. The bead should be in direct contact with the specimen but should be insulated from the band with a little asbestos and the two wires should touch neither the specimen nor the band. A couple attached in this way would satisfactorily measure the temperature of the specimen after the proper conditions have been attained and a comparison of the readings from couple No. 4 with readings from No. 3 during the survey will show how closely No. 4 can be relied upon to do so.

Couples Nos. 9, 10, and 11 are suspended in the medium surrounding the specimen and are for the purpose of indicating the temperature gradient from top to bottom of the furnace and to show how closely the specimen temperature agrees with the furnace temperature when equilibrium has been reached.

After the proper design of furnace has been attained there should be no temperature gradient within the specimen and only a very slight temperature difference between the specimen and the surrounding medium.

If it is deemed inadvisable to drill thermocouple holes in the holders intended for the actual physical tests, duplicate holders could be made up for the temperature survey.

In subsequent routine physical tests two thermocouples should be used, one at position 10 for furnace control and another strapped to the specimen as at position 4, to measure the temperature of the specimen. The difference between the readings from both will show when equilibrium has been reached. If auxiliary heaters are used around the ends of the holders or specimen projecting beyond the furnace two more thermocouples should be used to control the temperature in these heaters.

Mr. Moore. MR. H. F. MOORE[1] (*presented in written form by T. M. Jasper*). —In the paper by V. T. Malcolm, reference was made to the methods used by the Investigation of the Fatigue of Metals (University of Illinois, National Research Council, Engineering Foundation, and various cooperating firms) for making fatigue tests of metals at elevated temperatures. The results obtained to date are regarded as tentative, but as a matter of interest they are summarized in Table I:

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[1] Research Professor of Engineering Materials, University of Illinois, Urbana, Ill.

Mr. Moore.

TABLE I.—ENDURANCE (FATIGUE) LIMITS OF STEEL AT VARIOUS TEMPERATURES.

TEMPERATURE, DEG. FAHR.[a]	ENDURANCE LIMIT, LB. PER SQ. IN.[a]	TEMPERATURE, DEG. FAHR.[b]	ENDURANCE LIMIT, LB. PER SQ. IN.[b]
70	36 000	70	105 000
555	39 000	330	96 000
715	42 000	580	85 000
875	44 000	845	78 000

[a] 0.49-per-cent carbon steel, normalized; tensile strength, 88,700 lb. per sq. in.; Brinell hardness number, 164.
[b] 1.02-per-cent carbon steel, spring temper; tensile strength, 200,400 lb. per sq. in.; Brinell hardness number, 415.

The slight increase in fatigue strength up to 875° F. for normalized 0.49-per-cent carbon steel checks results obtained by Mr. Lea of Birmingham, England. It is suggested as a hypothesis that within the range of temperature studied, increase of temperature has two contradictory effects: (1) Increased temperature tends to soften the steel and hence to reduce the endurance limit; (2) increased temperature tends to increase the ductility of steel and to diminish internal strain, and tends to retard or even to inhibit the formation and spread of fatigue fractures, and hence tends to increase the endurance limit. For the 0.49-per-cent carbon steel the latter tendency predominates, and for the 1.02-per-cent carbon steel the destructive tendency predominates. Of course, further tests are necessary to give a satisfactory basis for any theory. Such tests are now in progress.

Mr. Speller.

MR. F. N. SPELLER[1] (*presented in written form*).—Lap-welded steel pipe for steam pipe in boiler plants is now made (under the A.S.M.E. Boiler Code Specifications) of low-carbon open-hearth steel with average analysis and physical properties (at normal temperature) as given in the following table, which also includes data regarding the same grade of steel to which ferrophosphorus was added in the ladle.

	Chemical Composition				Physical Properties			
	C	Mn	S	P	Tensile Strength, lb. per sq.in.	Yield Point, lb. per sq.in.	Elongation in 2 in., per cent	Reduction of Area, per cent
Regular Open hearth	0.09	0.44	0.034	0.013	50 690	29 730	42.0	67.7
Rephosphorized (Open Hearth)	0.09	0.43	0.050	0.103	61.120	38 785	37.0	63.8

The tensile strength of this steel at normal temperature compared with the strength at higher temperatures is shown in Fig. 12, expressed in percentage of the original strength at normal temperature.

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[1] Metallurgical Engineer, National Tube Co., Pittsburgh, Pa.

On the same chart is shown the strength of open-hearth steel of the same carbon content to which ferrophosphorus has been added in the ladle. These tests indicate that the latter retains a somewhat larger proportion of its original strength at the higher temperatures without much loss of ductility or resistance to impact. **Mr. Speller.**

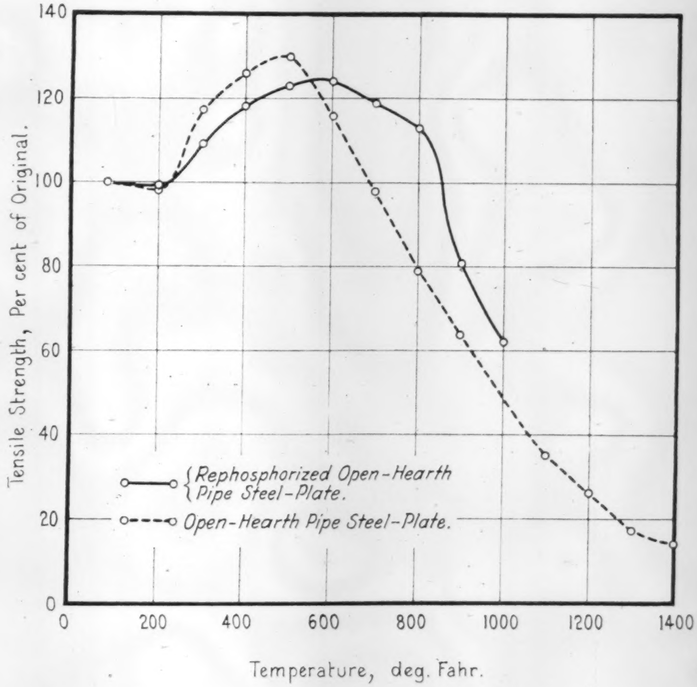

FIG. 12.—Effect of Temperature on the Longitudinal Tensile Strength.

The average tensile strength of these steels at 1000° F., as determined from this test, is as follows:

Regular basic open-hearth pipe	26 500 lb. per sq. in.
Rephosphorized pipe	36 000 " " " "

Attention is called to this, as phosphorus is one of the very few elements which can be added to welding steel without interfering with welding. Molybdenum seems to be another. In fact, the rephosphorized steel is easier and safer to forge weld, and apparently gives a sound steel equal to the regular open-hearth product with a much higher factor of safety. Endurance tests should be made on this steel.

Mr. Speller.

The investigation now being carried out by the Joint Committee on Investigation of Phosphorus and Sulfur in Steel should determine whether in fact these elements have any detrimental effect when added to low-carbon steel which is originally low in these elements. If not, in the interest of all concerned the question of revising American standard specifications with reference to the sulfur and phosphorus limits should be considered without further delay.

Mr. Schwartz.

Mr. H. A. Schwartz[1] (*presented in written form*).—The writer offers in Fig. 13 the results of tests made under his supervision by Messrs. W. W. Flagle and C. S. Fuller, which show the effect of low temperature upon the impact resistance of commercial malleable cast iron. These tests were made in connection with a problem which focused our attention upon the lower temperatures. They serve as a comparison, however, throughout at least part of the temperature range with the data of French and Tucker's Figs. 13 and 14.

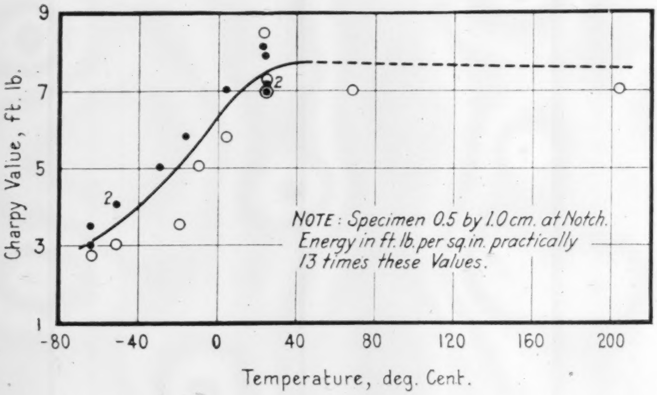

Fig. 13.—Notched-Bar Impact Resistance of Normal Malleable Cast Iron.

Open and solid circles represent metal from different sources.

It may be added that the results have been confirmed as typical of normal malleable cast iron by much other work in this laboratory. It is possible to produce malleable cast iron of still higher impact resistance by special methods, and equally possible to produce inferior material which suffers much more rapidly from brittleness as the temperature is lowered.

Mr. Puffer.

Mr. S. R. Puffer[2] (*presented in written form by S. A. Moss*).—In the various tests reported of the physical properties of steel at high temperatures, were the test specimens machined before or after heat treating? In other words, was any difficulty encountered in machining steel having high physical properties? **Mr. Puffer.**

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[1] Research Department, National Malleable and Steel Castings Company, Cleveland, Ohio.

[2] Thomson Laboratory, General Electric Co., Lynn, Mass.

In modern superheated steam and gas-turbine practice, it is very essential that the turbine buckets retain high physical properties at high temperatures. Dovetail shapes on such buckets are often very complicated. If heat treating is done after machining, hardening cracks are likely to be introduced. If machining is done after heat treating, will it not be necessary, in order to do the machining, to sacrifice a large percentage of the strength which might be available?

In Fig. 14 of the paper by French and Tucker, it is evident that high-nickel-chromium steel has excellent resistance to impact. Is any data available as to the tensile properties of this material at temperatures above 900° F.?

In Fig. 8 of the same paper, are shown two samples of tungsten high-speed steel, classified as B_1 and B_2, which show excellent properties at high temperatures. We understand that they have no elongation or reduction, even at the high temperatures, and are so hard that they could not be machined except by grinding. Is this correct?

Is any data available as to the high-temperature tensile properties of the high-nickel-chromium alloys, such as nichrome, chromel, etc.?

Mr. Strauss. MR. JEROME STRAUSS[1] (*presented in written form*).—The authors in their brief discussion of the chemical stability of steels and associated metals have touched upon a subject of extreme importance not only to the general engineering profession as we normally visualize it but of particular importance to the chemical engineer and his associates. Increased application, for production purposes, of high-temperature processes involving the reaction or production of chemically active materials, and the extension of the temperature and pressure ranges of these processes, have forced upon metallurgists the development of materials for progressively increased utility in these fields.

Even the service that has heretofore been obtained from ordinary metallic containers at atmospheric temperature no longer satisfies the requirements of continuous economical production. And in many cases metals have been required to withstand the action of corrosives through cyclic variations of temperature, pressure, and concentration over rather wide ranges.

The past decade has witnessed such rapid advances in the development of ferrous metals suitable under a wide variety of conditions

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[1] Material Engineer, U. S. Naval Gun Factory, Washington, D. C.

Mr. Strauss. of the above general nature, that the American Society for Testing Materials has seen the advisability of bringing together as much as possible of the available data on these new metals, and those which are at present in competition with them, in the form of a Symposium. A large number of papers have been secured for presentation at this meeting and it is believed that the discussion will be sufficiently extensive to create a broad fund of information relative to these metals. Mechanical, chemical, electrical and general physical properties are to be considered and, as an introduction, tables have been prepared giving manufacturer's data, in so far as available, concerning their various products. These tables should be of much value to the engineer in placing the entire commercial field before him and assisting in a selection of metals for specific applications.[1]

Mr. Fahrenwald. MR. FRANK A. FAHRENWALD.[2]—Referring to the paper by Messrs. French and Tucker, the writer believes greater emphasis should be placed upon the time factor as affecting the working strength of material at high temperature. The time factor as developed under tests running for only a short time does not give the effective strength of the material when subjected to stresses at temperatures above the recrystallization point.

Much of the information that has been hoped for and suggested by the various authors of these papers has already been worked out and has been available for some years to the trade. The physical strength of heat-resisting alloys at elevated temperatures has been determined in terms of permissible safe load stresses for use in design.

This property apparently has nothing to do with the elastic limit, nor is the modulus of elasticity in any way involved, and it seems that the fundamentals which govern the flow of viscous materials —such as ordinary road-paving pitch—have more to do with the behavior of these alloys at high temperatures than do the factors which we ordinarily associate with metals and alloys. A piece of road-paving pitch, placed between thumb and finger, can be slowly flattened with steadily applied pressure but if hit by a sharp blow with a hard object it will immediately fly to pieces like glass.

This same type of behavior seems to be common to metals and alloys as well. The rate of application of the load and the time during which it is applied are more important in determining the ability of an alloy to resist stress at high temperatures than all the other factors involved.

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[1] For the papers and discussions entering into this Symposium, see p. 189.

[2] Consulting Engineer, Cleveland, Ohio.

The writer has determined the high-temperature characteristics of various steels, and particularly of alloys for resisting chemical corrosion and mechanical stress at high temperatures, and while some of this information is bound up in proprietary interests and professional obligations, most of it is available to any one who cares to ask for it. **Mr. Fahrenwald.**

At high temperatures the relationship between the apparent mechanical strength of a metal or alloy as revealed in ordinary tension tests, compared with the ability of the same material to resist continuously applied stress, is truly surprising.

At 1750° F., for instance, the strength of the nickel-chromium alloy, under a quick-pull test, will be more than fifty times that under a stress extending over a period of a year.

Most of the data that the writer has developed in this line are not taken from laboratory tests, but have been interpreted from practical commercial operations and with this information it is possible to design beams or structural members for operation at any given temperature up to, say, 2200° F. with the same assurance of success that obtains in the design of ordinary mechanical structures.

Thermal expansion is perhaps one of the most powerful and destructive agencies encountered in mechanical operations at high temperatures, due to dimensional changes that accompany changes in temperature.

In even the most simple mechanisms it is almost impossible to prevent temperature differentials of from ten to several hundred degrees between one point and another on the same alloy unit and as a result the cold part is under tension and the hot area under pressure with resulting plastic flow under either tension or compression, followed by a reversal of stresses perhaps with further temperature changes and final failure. Here is a problem of fatigue from alternating compression and tension beyond the plastic deformation limits of the material, and whether this corresponds to fatigue as we ordinarily understand it the writer does not know.

The problem of the application of metals and alloys at high temperatures is far more complicated and difficult than is ordinarily supposed. If physical strength or chemical resistance or thermal expansion or elastic limit or any one single factor is considered without correlating it to all of the other factors of the problem, failure will result.

These remarks may confuse the issue rather than clear it up, but this phase of engineering is indeed very complicated and anything

Mr. Fahrenwald. that will serve to call attention to the need for considering and correlating the numerous essential factors will be of help.

Mr. Christie. MR. A. G. CHRISTIE[1] (*presented in written form*).—The summary of the principal published work on the strength of non-ferrous alloys at various temperatures as presented by the authors indicates the increasing demand for alloys which will exhibit properties required by designers of apparatus which is stressed at high temperatures. The ideal condition as regards the strength of the material used in apparatus, such as valves and fittings, operating under superheated steam conditions would be that the physical properties remain constant from room temperature up to some point above the range of the temperature of operation. It is obvious that with such material the designers could be assured that no failure due to weakness would develop when the temperature is increased from normal to 800 or 900° F., which is above present operating temperatures.

In connection with securing data on such properties, it should be noted that where the curve of the elastic limit is falling off rapidly with increasing temperature, a slight experimental error in the measurement of the true temperature of the specimen affects its value for a given temperature to a very great degree. While allowance could be made by the designer for the decrease in strength of a material in which this property is affected by an increase in temperature as is the case in many steels and ferrous alloys, it is apparent from a study of the result of methods of testing and of values presented for various materials of this type that it is difficult to arrive at the exact amount of decrease of strength for a given temperature. Hence, it would be very much safer to use a material for which the curve of the elastic limit is nearly flat throughout the range of working temperatures.

Other considerations governing the choice of material by the designer or operator for valves and related parts subject to high temperatures are freedom from oxidation or corrosion and ability to grind the seat with facility.

Mr. Mochel. MR. N. L. MOCHEL[2] (*by letter*).—Referring to the paper by Messrs. Upthegrove and White, it may be of interest for us to record a peculiar type of failure which is apt to take place in the use of copper-tin alloys at elevated temperatures. A number of curves are given for copper-tin and copper-tin-zinc alloys, and in general there is a marked change, a sudden drop or a more rapid falling off in strength in the neighborhood of 450 to 500° F.

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[1] Consulting Engineer, Curtis Bay Copper and Iron Works; Professor, Mechanical Engineering, Johns Hopkins University, Baltimore, Md.

[2] Metallurgical Engineer, Westinghouse Electric and Manufacturing Co., Philadelphia, Pa.

Mr. Mochel.

Fig. 14 is a micrograph (×75) of a specimen of drawn phosphor bronze, containing 2 per cent tin and low phosphorus, after service for one year at 650° F. The stresses were quite low. There is a peculiar intercrystallin action which has taken place at the surface and is rapidly growing inward. The same condition has been observed on similar material after service at 500° F. The action has not been limited entirely to the drawn material, but has been observed as well on cast bronze of the 88-10-2 type, resulting in a falling away or deterioration of the metal and in the carrying away of "chunks" of the material, or its absolute failure. The action seems to be peculiar to those alloys of copper with low-melting point materials such as tin, although quite similar deterioration has been reported with copper-aluminum alloys at approximately 500° F. The action is marked by an embrittling of the affected material.

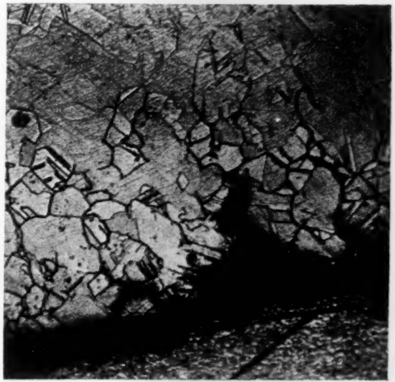

FIG. 14.—Micrograph of Specimen of Drawn Phosphor Bronze.

The short-time tests may show fair strength for certain materials of the type mentioned above, at temperatures above 500° F., but deterioration is an item and must be considered.

It is also felt that a valuable and interesting addition to the Bibliography would be a paper presented before the Institute of Metals, in March, 1924, by Bunting, on "The Brittle Ranges in Brass." It has been summarized as follows:

"The brittle ranges exist in brasses of composition varying from 90 to 52 per cent copper. The brittle range of the 52-per-cent alloy extends from 220 to 540° C., and as the percentage of copper increases the range reaches a minimum at 57.5 per cent copper, extending from 320 to 450° C. With further

Mr. Mochel. increase of copper the range extends upward indefinitely, and at 65 per cent exists from 325° C. until the solidus is entered. At 75 per cent an upper limit to the range is once more observed, the range now extending from 350 to 725° C. Beyond this point the lower limit (hitherto practically constant at 325° C.) rises until at 80 per cent the range extends from 430 to 630° C. The range now narrows, and finally terminates in the neighborhood of 90 per cent."

Mr. Elliott. MR. GEORGE K. ELLIOTT[1] (*presented in written form*).—There is need of close cooperation between chemist and metallurgist in our present problem of metals for high-pressure and high-temperature steam. At present the metallurgist is given little other information than the temperature and the pressure at which the central station is to be operated, and possibly this information is sufficient, but the writer for one would like to have fuller data concerning the chemical composition of this new steam which our metals are to handle.

Endless literature has been written about the chemistry of the boiler and boiler waters and the most of it is of great value, especially in studying corrosion, but if we search for information concerning the chemical reactions which do or are likely to take place in boilers operating at the new pressures of 400, 600, 900 lb. per sq. in. or even higher, we are doomed to disappointment; little is available. The reason for laying stress on this is that the writer feels insufficiently assured that the chemical reactions taking place in water containing certain dissolved salts and gases, at 100-lb. pressure and 337° F., are going to take place when the pressure is raised to 400 or 600 lb. and the temperature to 750° F. Will the steam generated under the new conditions contain compounds which were not present in the vapor from the old-fashioned boilers?

Only one possible but admittedly speculative condition will be given as an example. Some investigating chemist in England, I believe, has made somewhat of a study of this new boiler chemistry and is on record as having evidence that alkaline boiler water containing sodium carbonate, for example, under certain conditions of concentration, pressure, and temperature, will react to form a series of organic acids such as formic, glycollic, and others of a series made by successive deductions of an atom of oxygen from the compound. This is extremely interesting if true, and even more so when we are told that there is a possibility that volatile organic compounds of a corroding nature such as formaldehyde may be formed in the boiler. If, therefore, it is discovered that corrosive compounds of a kind hitherto unknown to boiler chemistry are likely to be formed in high-pressure boilers, the metallurgist should have definite information concerning the exact nature of these new ingredients in the steam to be handled by this metallic piping, valves, fittings, and turbines. **Mr. Elliott.**

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[1] Chief Chemist and Metallurgist, The Lunkenheimer Co., Cincinnati, Ohio.

It may be that there is no real cause for alarm, but the writer would like to see the question of boiler-water chemistry thoroughly studied by competent chemists, preferably organic chemists, since the reactions foreseen are of a decidedly organic chemical nature. There is a probability that the new high-pressure boilers are chemical manufacturing units, operating on the dissolved substances of the water, in which a great number of complex reactions probably take place with the production of many compounds, some of which may well be viewed with suspicion by the metallurgist who is prescribing metals to handle these chemical products when mixed with steam.

Once the program of purely chemical research is completed, and the chemical nature of the impurities in steam generated at high pressures and then superheated is determined—if such impurities be found—obviously the next step would be to conduct high-temperature physical tests with the test pieces immersed in atmospheres which are similar to the steam we are describing. This would add immeasurably to the labor and time necessary for making these tests, especially the time, for time would be important directly in proportion to its duration; but the results might well prove to be worth all the trouble multiplied many times. The writer is not ready to predict how important the matter of surrounding atmosphere may be in making these high-temperature tests upon all the metals and alloys now used in handling steam, but it has been demonstrated by Bengough and Hanson that in the matter of copper it is of the greatest importance. So-called season cracking, so frequently met with in wrought non-ferrous metal, also is somewhat related to the point of this discussion. It was shown some years ago that this kind of metal failure has its beginning with surface corrosion of the piece under stress, the corrosion being caused often by gaseous impurities of a corrosive nature in the surrounding atmosphere.

To sum up, the writer suggests the following research:

1. That chemical reactions in high-pressure boiler water and in superheated steam, up to 800° F. be investigated;
2. That, if corrosive compounds are found to be a possibility in such steam, high-temperature physical tests be made with test specimens surrounded by an atmosphere similar to this steam.

Mr. MacPherran. MR. R. S. MACPHERRAN[1] (*presented in written form*).—As many plants are operating with steam at from 800 to 850° F., it is necessary

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[1] Chief Chemist, Allis-Chalmers Manufacturing Co., West Allis, Wis.

Mr. MacPherran. for us to know the properties of materials at these temperatures. Until recently, most high-temperature testing was done by heating the specimen until the desired temperature was reached, and then running the usual tension test. As referred to in these papers, however, Mr. Dickenson has made a series of most interesting tests by maintaining a constant load and a constant temperature until failure of specimen. We are preparing to make tests along these lines and hope to work under various temperatures and loads.

We are now making some tests along a little different line by holding the specimen at constant load and slowly increasing the temperature until failure occurs. In each test, the specimen was held at a definite temperature until the beam remained in balance for 15 minutes. This would allow for any expansion due to increased temperature, and for any extension which might take place in this short period. The final period or period of maximum temperature before failure at this increasing temperature and constant load lasted several hours or more. For example, one specimen was held at 1000° F. under a load of two-thirds of its elastic limit for over 15 hours before it finally failed. The load was maintained, of course, during the entire test by keeping the beam in balance as the specimen elongated. While our results in these tests have been very interesting we are not yet in a position to report.

We would be much interested in learning how the various bronze test specimens were prepared. Were they cast or rolled? And was any trouble found in obtaining a uniform material? We have cast several sets of bronze bars for high-temperature tests but find great difficulty in obtaining specimens of the necessary uniformity for a series of these tests.

One of the most interesting ideas in this discussion is that advanced by Mr. Elliott.[1] We have all seen examples of steam corrosion for which there seemed to be no explanation or definite cause. It is possible that investigation of the chemical combinations formed in the boiler under high temperatures and pressures may lead to the solution of some of these problem.

Mr. Lincoln. MR. J. C. LINCOLN[2] (*by letter*).—This contribution to the discussion is at the request of the American Welding Society. It has to do with the action of metal deposited by the metallic arc and the effect of repeated heating on such metal. The metal deposited by the metallic arc process has a tensile strength of about 50,000 lb. per sq. in., if properly deposited. The ductility of this metal is low, about 5 per cent.

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[1] See preceding discussion.

[2] Lincoln Electric Company, Cleveland, Ohio.

Mr. Lincoln.

Repeated heating of such weld metal in an oxidizing atmosphere at a temperature of about 1550° F. changes the structure of the weld metal and decreases both its strength and ductility. So far the writer has been unable to assign the cause for the change in structure and for the change in physical properties. If anyone has done any work along this line and can throw some light on this problem, he will be doing the art of electric welding a service.

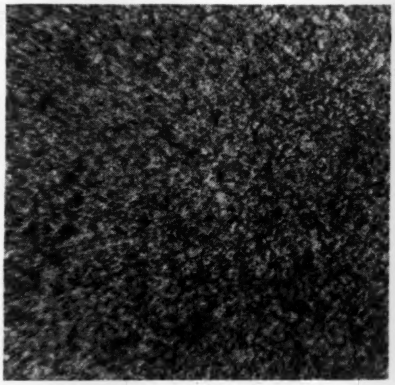

FIG. 15.—Microphotograph of Metal Deposited by Metallic Arc, After Polishing and Etching (× 100).

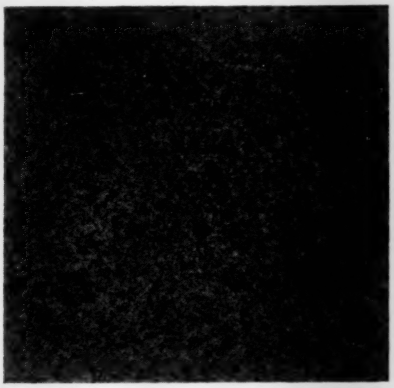

FIG. 16.—Microphotograph of Same Metal, After Repeated Heating at About 1500° F. (× 100).

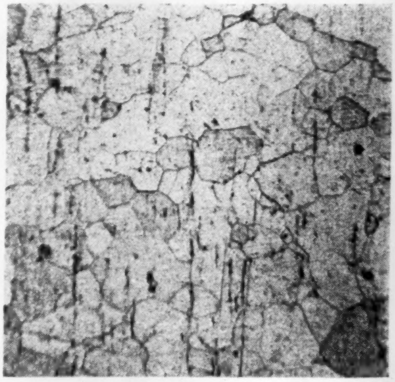

FIG. 17.—Microphotograph of Ordinary Open-Hearth Low-Carbon Steel, Exposed to the Same Heating and Cooling (× 100).

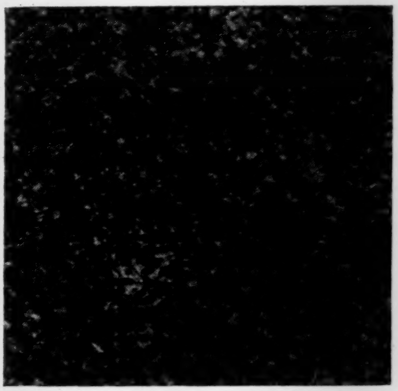

FIG. 18.—Microphotograph of Same Metal, After Repeated Heating at About 1500° F. (× 200).

Fig. 15 is a microphotograph of metal deposited by the metallic arc after polishing and etching.

Mr. Lincoln. Fig. 16 is a microphotograph of the same metal after repeated heating at about 1500° F.

Fig. 17 is a microphotograph of ordinary open-hearth low-carbon steel after having been exposed to the same heating and cooling that produced the change in structure shown in Fig. 16.

Fig. 18 is a microphotograph of the same sample shown in Fig. 16, except that the magnification is 200 diameters instead of 100 diameters.

Mr. Moss. MR. SANFORD A. MOSS.[1]—The temperatures of 700 to 800° F. mentioned in the papers are really quite moderate. Mr. Emmet[2] mentioned temperatures of 1000° F. in connection with the mercury turbine. There now exist a number of gas turbines in series with internal-combustion engines, with wheel rotating at high speeds, and operating at temperatures of about 1000° F. Hence, the authors of the various papers must not stop at 700 or 800° F. but must go on.

One important point is proof that the specimen has the temperature alleged. Many of the tests in the bibliography cited are worthless because there is nothing to show that they do not fall in the large group of tests with erroneous temperature measurements. One way to be certain that the specimen has the supposed temperature is to make two separate sets of tests with two separate furnaces, one with a certain length of furnace and specimen, and the other with the same length of specimen and a longer furnace. If the same results are obtained reliance can be placed on them. No high-temperature tests can be given credence unless there is given actual proof in some such way of the validity of the temperatures.

It is quite possible that the time element which has been mentioned is largely a matter of thermal equilibrium. In other words, it may be that some of the experimenters who have thought that their results showed the effect of the time element really did not have conditions of thermal equilibrium originally, so that the effect was one of temperature measurement error only. The certainty of the time element can be established only when it is first proved that the temperature of the specimens is the temperature alleged.

Very little attention has been paid to the hardening and drawing temperatures for the ferrous materials tested. It is probable that, in order to secure the best performance at given high temperature, there must be quite a different combination of hardening and drawing temperatures than for some other temperatures. This, of course, opens up a vast field for research. In other words, it is possible that for every temperature of use of ferrous materials, there must be a special hardening and drawing temperature.

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[1] Engineer, Mechanical Research Department, General Electric Company, West Lynn, Mass.

[2] Discussion of paper by V. L. R. Emmet, "The Emmet Mercury-Vapor Process," *Transactions*, Am. Soc. Mechanical Engrs., Vol. 46 (1924).

Mr. Moss. The matter of the effect of the atmosphere on the testing has been mentioned. It is sufficiently difficult to make tests at high temperature without the added complication of having to maintain a certain atmosphere. The only materials in which we are interested for high temperatures are materials which will not be affected by the atmosphere. An independent set of tests could be made at high temperature in a given atmosphere, without any tension tests, simply to establish as to whether or not the material was affected. If it is found that the material is affected at the temperature involved, there is really little use of making further tests. If it is found that the material is not affected, then the high-temperature tension tests may be made.

Mr. Funk. MR. NEVIN E. FUNK.[1]—This Symposium adds to our knowledge of the performance of materials at high temperatures, but the writer questions the advisability of using the exact values given on account of the fact brought up by other discussers, that it may not be possible to duplicate the results with different apparatus.

Since we are following practice with knowledge rather than knowledge with practice, and since the possibilities of considerably higher temperatures are of great interest in obtaining better efficiencies, material manufacturers should not consider the problem solved, but should endeavor to produce materials that will withstand these high temperatures better than the ones that are now available.

This Symposium apparently does not contain information as to the effect of temperature variations over a continuous period on the performance of these materials.

It is generally known that cast iron, unfortunately, grows at temperatures as low as 550° F. so that in, say, eight years' time, parts made of that material must be replaced. With these higher temperatures, the same thing may happen to steel or steel alloys. We have not yet had enough practical experience to know, but the field should be investigated.

The effect of oxidation on these metals at high temperature has been touched upon. If the higher temperatures produce more rapid corrosion, the factor of safety may soon become inadequate.

While all the information that has been presented is valuable as an indication of the trend of the subject, so far as the writer's personal feeling is concerned, only a beginning has been made toward the developments necessary to the intelligent design of higher temperature stations and the certainty that the life and safety of these stations will be as accurately anticipated.

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[1] Operating Engineer, Philadelphia Electric Company, Philadelphia, Pa.

Mr. Orrok. MR. GEORGE A. ORROK.[1]—From the standpoint of the power engineer this subject presents three distinct problems dealing with (1) the turbine blade and the interior of the turbine, which remain at practically one temperature as long as the machine runs; (2) the boiler, whose external temperature may be quite high while its internal temperature is limited to the steam temperature used; and (3) the steam pipe, in which the internal temperature is fixed while that outside varies.

In regard to the first of these problems, materials which we have been using apparently stand any temperatures that have been attained so far and probably materials can be obtained which will permit turbine blades to be operated up to 800, possibly 900° F. Whether we shall be able to find materials for the gas turbine with its higher temperatures is something to be worked out.

As for the boiler, the outside of the metal may be heated to almost any degree. The writer recently had the opportunity of looking into a boiler where the internal surfaces were at a bright red heat. Probably the temperature of those internal surfaces was 900 or 1000° F., since the temperature inside the boiler was about 850° F. What happens in such cases is not known and much good work must be done before reliable information can be obtained.

Regarding the steam piping, it appears that materials are fairly well understood and perhaps pipe manufacturers will be able to provide almost anything that may be needed in the next twenty-five or thirty years.

One of the particular things in this kind of research is getting specimens of material which are alike and in duplicating them in the actual material that we buy to put into our plants. The writer is very certain that most of these specimens which have been tested, while ostensibly of a reasonably close chemical composition, are not alike, and probably two pieces cut from the same bar will show rather wide variations, both in chemical composition and in crystallin structure.

Mr. Robinson. MR. ERNEST L. ROBINSON.[2]—The writer calls attention to a point which has not been emphasized elsewhere in the Symposium, namely, the importance of the effect of temperature on the modulus of elasticity. The other discussions deal with questions of strength, proportional limit, and extension, but in tuning a turbine wheel so as to control its natural frequencies of vibration, it is important to have information as to the modulus of elasticity. We have thought here-

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[1] Consulting Engineer, New York City.

[2] Turbine Engineering Department, General Electric Company, Schenectady, N. Y.

Mr. Robinson. tofore that, throughout the temperature range to which turbine wheels are subjected, the change in modulus of elasticity is so gradual as to be of little importance. But some of the curves presented in these papers show rather sudden changes in the modulus. If these indications are substantiated, it will be important to give attention to the modulus in future investigations of the effect of temperature on steels.

Mr. Trump. MR. C. C. TRUMP.[1]—To Mr. Orrok's three and Mr. Robinson's one problem the writer would like to add a fifth. That is the problem of the oil refinery which has been referred to already in the papers. We not only have boilers, turbines and piping for steam but we also have stills which carry oil vapors at increasingly high temperatures and pressures. Within those oil vapors are associated not only high temperature and pressure, but also corrosive media such as sulfurated hydrogen and other gases which at those temperatures do attack the metals. In fact, they attack them to such an extent that we have to make our pipes thick enough to withstand a considerable reduction in thickness. Our problem of strength is one of years. We want to know about strengths of material at high pressures, and we hope that there will be further information coming along these lines.

Another point in which we are interested is the growth of materials other than cast iron, especially of the non-ferrous metals, because we sometimes want to use non-ferrous alloys in our valves and fittings. There is nothing in any of these papers concerning the growth of materials other than cast iron.

Mr. Hoyt. MR. SAMUEL L. HOYT.[2]—The writer would like to point out a certain relationship which he believes to be a general one connecting the load on a specimen and the life of the specimen at that load.

He first experimented on tin, a metal which is fairly soft and plastic at room temperature, with loads varying over a considerable range, so that the time element varied from less than one second to over a million seconds. In order to interpret the data he plotted them two or three different ways and finally found that if the logarithm of the time were plotted against the square root of the load the result was a straight line. That such a straight-line relationship is desirable can be shown very briefly.

According to one method of plotting the data, all of the points came on a smooth curve. When the data were plotted as a straight line it was noticed that the time for some of the loads was twice what it should be, according to the straight-line relationship. By exam-

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[1] Engineer of Tests, The Atlantic Refining Co., Philadelphia, Pa.

[2] Research Laboratory, General Electric Co., Schenectady, N. Y.

Mr. Hoyt. ining the samples it was seen that they had fractured according to a different method than the samples which had longer lives. This indicates that tin extends and fractures according to two different mechanisms, depending on the rate of deformation.

The writer has also noticed a difference between cold-worked metals and annealed metals in the way they follow this relationship, and, further, that the relationship holds over a wide range of temperature. He has examined tungsten at high temperatures and is beginning to examine iron and other metals at a somewhat lower temperature. From these observations the relationship seems to be a general one.

The writer suggests that those who are interested in this particular feature plot their data as the square root of the load against the log of the time. In that way, if there are any exceptional conditions present they will probably be brought out at once by the fact that the points do not fall on the curve or do not come as close to the curve as they should according to the experimental error involved.

A long-time test at a high temperature is not a simple thing, but if we knew that this relationship held, it would be possible to extrapolate from high loads, in order to get the probable life at low loads.

Mr. Templin. MR. R. L. TEMPLIN.[1]—We have been taking temperature tension tests on aluminum and some of the alloys of aluminum from time to time during the past five years. In general our results on pure aluminum check fairly well those given in the Symposium.

In connection with such tests it should be noted that in the material which was used by Messrs. Upthegrove and White there existed an appreciable amount of cold work. If the material had been annealed to start with, the tensile strength curves would not be parallel to the curve given in their paper. If the plotting of the data, however, is done so as to give the ratio of the tensile strength at any high temperature to tensile strength at room temperature, there would be fairly close agreement of results. That is, differences due to different amounts of cold working and perhaps even variations in composition of the material will be practically eliminated by such a method of treatment, usually in a very satisfactory manner.

It has been observed that tests on the cold-worked metal tend to give higher values for the range of temperature in which we are normally interested for design purposes. It is thought, however, that if the specimens were maintained at these higher temperatures for a considerable period of time, varying with the temperature, the values obtained would approach those which are normally obtained, starting with annealed material. **Mr. Templin.**

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[1] Chief Engineer of Tests, Aluminum Co. of America, New Kensington, Pa.

In addition to the work that has been done on pure aluminum, we have done some work comparatively recently on pure magnesium and one of its alloys. In connection with these tests, it has been interesting to note that while we obtain one set of data with pure magnesium and another set of data with a magnesium alloy consisting approximately of 4 per cent aluminum, yet when treated in the manner just indicated, the tensile strength results are identical.

In applying these data in a practical way our inclination is first to evaluate the effects of temperature upon the material, then for design purposes to use in our formula the annealed tensile strength of the material at room temperature and show the effect on it rather than to take the tensile strength of some harder or cold-worked metal and depend upon that as the basic value.

We have run into serious difficulties in our methods of testing because the materials with which we have been concerned have a rather high thermal conductivity. This, of course, tends to decrease the difference in temperature that exists between the center of the specimen, say, and the outside surface, but at the same time it is harder to keep the temperature uniform throughout the length of the specimen. Again, the values for ductility or elongation are rather high in these materials, running sometimes over 200 per cent. That means that furnaces used in testing them must be quite long in order to maintain the specimens at the desired temperatures throughout.

We ordinarily consider these data as being roughly divided into two phases. The first is the one which extends usually to about 400° C. Temperatures from below room temperature to this point are the ones which concern the designer. Those beyond that point are usually of prime interest only to the manufacturer of such materials.

Mr. Jeffries. MR. ZAY JEFFRIES.[1]—Probably in all the fields for the use of materials at high temperature there is none in which so much effort has been spent as in the electric-lamp field. Artificial illumination with incandescent lamps depends upon the maintenance of a body at a very high temperature and for a considerable time. The tungsten filaments used in incandescent electric lamps sometimes reach a temperature of 2900° C. and are maintained at that temperature over a period of at least 100 hours, and some lamps with a temperature of 2700° C. may maintain their temperature for 1000 hours.

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[1] Metallurgical Engineer, Research Bureau, Aluminum Co. of America, Cleveland, O.

Mr. Jeffries. The material used is nearly a pure metal, about 99.9-per-cent tungsten. The writer calls attention to the effect of grain size on the maintenance of the characteristics of the metal at a high temperature. If the grains are maintained small at the high temperature the filament sags during the course of its use and the coils get out of shape. If a special treatment is made so that a larger grain size is produced, the elastic limit of the material is relatively high at a temperature just under the melting point and the coils maintain their positions. That has been found generally true, not only in tungsten but in other metals, and would indicate that at very high temperatures we should strive to obtain large grains in pure metals in order to maintain permanency of shape of the material.

There are so many complications in the temperature effects of pure metals that one hesitates to bring in the added complications of alloys, but they must be considered because they are important commercially. In alloys, the inter-metallic compounds are the hard constitutents at high temperatures. They correspond in high-temperature properties more to the non-metallic substances like fire clay or silica. They are the hard bricks which strengthen the soft metallic matrix in materials at high temperatures.

The writer compliments Mr. Wilhelm upon the determination of the proportional limit and the modulus of elasticity of steel at various temperatures. The subject of the modulus is one which has been worrying people for a long time, and the true proportional limit is one which is masked by the blue heat effect in iron. His results are certainly the best that have been seen in that field, and the writer looks forward to seeing further results from the same apparatus.

In conclusion the writer suggests that the general research be divided into two groups, as follows: First, the fundamental properties of materials at high temperatures, which may be carried on by the metallurgist and chemist; and second, the use of materials at high temperatures. The latter study may involve tests simulating use tests, and should be made by the engineer who is in close contact with the actual utilization of the metals at high temperature.

Mr. Mathews. MR. JOHN A. MATHEWS.[1]—As manufacturers of these materials, we have found some which proved to be tough at the lowest temperatures and malleable at liquid air temperature, while others showed only an oxidation film (similar to the temper colors of a tool) at 2200° F. We have worked out a series of them for various conditions of corrosion, a point that has been only slightly touched upon in this Symposium.

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[1] Vice President and Metallurgist, Crucible Steel Co. of America, New York City.

Mr. Mathews.

There is no one material that will answer all purposes. For each of the milder acids—acetic, formic, lactic and butyric—we must meet the condition of maximum serviceability through special compositions. We have studied our products one at a time to attain maximum resistance to corrosion for scores of reagents under various concentrations and temperatures. In some cases a single material answers for many of them but not for all. For use at temperatures from 700 to 1600° F. these nickel-chromium-silicon alloys, known under the trade name of "Rezistal," seem to be stronger, tougher and more resistant to fatigue than any other type of ferrous or non-ferrous alloy.

Mr. Spring.

MR. L. W. SPRING (*Author's closure*).—In discussion, several have referred to possible inaccuracy of results due to uneven heating of the specimens, loss of heat through conduction, difficulties of temperature measurement, etc. I think that no one realizes more than the investigator himself, who has tried to do some of these things and to do them as accurately as he can, the difficulties that are in the way of obtaining accurate physical properties of materials at high temperatures. One would be unwise to claim that any of the work done is perfect. Since all who have worked in the high temperature field have proceeded along more or less different lines, and since, therefore, there has never been anything like a standard method of making such tests, it is highly desirable that some properly formed committee very carefully work upon and determine the most satisfactory method or methods of high temperature testing, so that, hereafter, such routine testing may be done according to something like standard methods.

A point was made by Mr. Herman Holz regarding the possible effect of magnetic induction upon the results. Years ago in our laboratory we made tests along that line, using coils that were exact duplicates, except that one was our usual heating coil of nickel-chromium or nickel wire and the other coil was wound with pure copper wire, which gave only 12° F. rise in the bar, when using much greater amperage than we ever applied in actual work. These results were reported in 1912[1] but are repeated here in the accompanying Table II. As is shown by the figures, on neither brass, bronze, ferro steel, nor cast iron do results differ from results obtained without any coil at all, showing that the effect of induction is negligible.

Mr. Morrison referred to insulation of the holders. I believe that such has not been done commonly, so the holders and heads of the testing machines are constantly conducting away considerable amounts of heat, which, of course, means less equal temperature throughout the length of the bar or at least difficulty in maintaining equal tempera-

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[1] *Valve World*, January, 1913; Also References **83** and **216** of the Bibliography appearing on page 128.

TABLE II.—EFFECT OF ELECTRICAL CURRENT WITHOUT HEAT ON STRENGTH OF TEST BARS.

Material	Test	Tensile Strength, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent
Crane Valve Brass	Test I[a]	30 800	19 900	12.5	21.8
		30 800	18 900	18.8	19.2
		Average 30 800	19 400	15.7	20.5
	Test II[b]	31 600	18 775	15.6	19.6
		30 800	19 150	15.6	19.3
		Average 31 200	18 960	15.6	19.5
	Test III[c]	30 120	18 180	12.5	......
		Average 30 120	18 180	12.5	......
	Test IV[d]	32 300	21 000	15.6	18.9
		32 000	19 600	14.1	16.5
		Average 32 150	20 300	14.9	17.7
Crane Hard Metal	Test I[a]	38 500	23 430	7.8	14.6
		36 700	26 010	9.4	16.3
		34 180	27 000	9.4	15.1
		Average 36 480	25 480	8.9	15.3
	Test II[e]	35 350	......	9.4	......
		36 950	23 130	9.4	13.9
		37 100	26 745	12.5	16.6
		34 200	27 600	6.3	9.9
		Average 35 910	25 825	9.4	13.5
Crane Ferro Steel	Test I[a]	39 135			
		35 130			
		32 710			
		36 920			
		37 210			
		Average 36 220			
	Test II[e]	38 640			
		40 270			
		35 900			
		38 000			
		34 650			
		Average 37 490			
Crane Cast Iron	Test I[a]	23 700			
		21 960			
		Average 22 830			
	Test II[e]	21 750			
		23 800			
		Average 22 775			

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[a] Without coil.

[b] With copper wire coil; $\frac{1}{2}$ ampere, 690 ampere turns. Broke at once.

[c] With copper wire coil; $\frac{1}{2}$ ampere, 690 ampere turns. Current on 5 hours.

[d] With copper wire coil; $2\frac{1}{2}$ amperes, 3450 ampere turns. Broke at once.

[e] With copper wire coil; 1500 ampere turns.

tures. Of recent years we have interposed horizontal disks of asbestos $\frac{1}{2}$ in. thick between the ends of the bar and the machine heads as shown in Fig. 9 on page 26. These disks are held between 6-in. cast steel flanges, the bolts of which are also insulated from contact with the flanges by asbestos winding. **Mr. Spring.**

In many of our tests, the bottom of the hole which is drilled axially into the bar, as shown in Fig. 8 on page 25, contains two or three drops of metallic mercury to insure perfect contact of pyrometer tip with the bar itself. This eliminates any possibility of getting incorrect readings because of poor contact.

We have been using the gap wound coil, also shown in Fig. 8. With coils wound over their full length we found it almost impossible to avoid a higher temperature in the center of the breaking section of the test bar than at the ends. Part of this variation may be attributed to conduction or radiation of heat from the ends of the test bar. By using a coil with a 3-in. gap over the breaking section of a calibration bar drilled axially all the way down to the lower shoulder, the pyrometer tip showed very close temperature readings at lower shoulder, the center of the breaking section, and the upper shoulder where temperatures usually were taken.

Mr. Malcolm. MR. V. T. MALCOLM (*Author's closure*).—I have been very much interested in the various comments regarding the details of the test methods and in the several suggestions that have been made. Mr. Wilhelm is to be congratulated on the thoroughness of his work in this field of research. However, we must keep in mind that our tests must be as simple as possible because they are destined to become routine tests in the laboratories of the producers of high-temperature materials. In fact, this is true to some extent to-day; certain specifications now require that several test bars from each lot of steel of 200 lb. or over be tested at elevated temperatures. There is considerable difference between research and routine testing. For routine work apparatus must be developed that is accurate within certain limits and with which tests at elevated temperatures can be readily made.

In the entire discussion very little attention was given to the condition of the material before test. I believe this is one of the most important points to be taken into consideration if reliable results are to be obtained, for the reason that inclusions, gas pockets, segregation, etc., tend to give false results. The structural composition, both before and after testing at various temperatures, should be investigated, because we know that structural changes take place at elevated temperatures, especially in the non-ferrous materials. Elevated tem-

Mr. Malcolm. peratures, combined with corrosion or a cycle of normal temperatures, then elevated temperatures and back to normal, will give results quite different in service than with the use of elevated temperatures alone. Laboratory tests should be compared with actual service conditions and the results carefully studied and tabulated for use.

Mr. Lester's remarks regarding the X-ray method of test are quite pertinent. The writer is personally familiar with Mr. Lester's work, and is in a position to appreciate the value of the X-ray as applied to testing of steel.

Mr. Holz's references to certain apparatus and especially his remarks regarding routine testing are to the point and the writer hopes that he may have the opportunity of studying the methods described by Mr. Holz.

Mr. Marsh's discussion regarding temperature differences is one that is of vital interest to investigators carrying out this type of work, as the proper location of the thermocouple is of great importance in the reporting of reliable results and this is a matter for further study as well as the means of reaching thermal equilibrium so that there will be no doubt as to the correctness of the temperature of the material under test.

A point which has not been touched upon is the use of steel and a non-ferrous alloy together at elevated temperatures. The writer believes that this should be given careful consideration on account of the difference in the coefficients of expansion. For example, in a cast steel valve with a bronze seat ring, the difference in coefficients of expansion between steel and bronze at a temperature of 750° F. is so great as to cause the bronze ring to be stressed beyond its elastic limit and when the temperature returns to normal the ring would be loose and probably fall out. The improper application of some materials for services for which they are totally unsuited is the cause of a number of failures.

Mr. French. MR. H. J. FRENCH (*Author's closure*).—I think especially interesting is Mr. Hoyt's suggestion regarding the straight line relations between load and time of failure in metals. It may at some time clear up very readily for us, in tests made in the laboratory, some of the questions relating to practical service.

I would like for a moment to refer to points raised in presentation of Mr. Puffer's discussion. A question was asked regarding the machineability of the various heat-treated steels. Following the hardening operation, which we shall assume momentarily fully hardens the steel, it is necessary to temper at a temperature somewhat in excess of the service temperature for stability. If the steel is merely hard-

Mr. French.

ened and we then attempt to make use of it at high temperatures, say in the neighborhood of 1000° F. or above, the tempering will automatically take place in service and in many cases undesirable effects may be observed. The ordinary structural steels are of such a nature that a temperature of about 1000° F. or above will materially soften the alloy and leave it in a machineable condition. In the case of hardened high-speed steel somewhat higher tempering temperatures are necessary to effect this softening. Steels B1 and B2 of Fig. 8, referred to by Mr. Puffer, are not in an initially machineable condition. They have fair ductility, at least consistent with such high tensile strength values in ferrous alloys. These results were included only for comparison with the more complete data for annealed steels given in the same figure, and as already pointed out tensile strength values in short-time tests are not proper criteria for design purposes.

Reply to the question regarding the tensile properties at tempera-tured above 900° F. of a high-nickel-chromium steel similar to that in Fig. 14 may be found by referring to the Bibliography and the index to the Bibliography presented as a part of the Symposium.

The same applies to the last question having to do with the tensile properties of high-nickel-chromium alloys. However, it may be stated that we are now making a series of high temperature tests on a wide range of compositions in the nickel-chromium-iron series including both commercial and special alloys.

In reference to the remarks of Mr. Moss, it has already been mentioned that tempering subsequent to hardening must be carried out at temperatures at least equal to and generally above the proposed service temperature to produce stability. Attention should also be called to the fact that the weakening effects of high temperatures tend to diminish differences observed between different materials or treatments at ordinary temperatures. That, therefore, has a direct bearing on what we can do by varying hardening heats to produce exceptional properties in a given alloy. In other words by varying the hardening temperature and subsequent tempering we may produce very different results at ordinary temperatures but the necessity of tempering at or above the service temperature for stability and the weakening effects of temperatures in the neighborhood of 1000 to 1600° F., for example, limits materially what can be done by varying preliminary heat treatments. These features are more carefully discussed at some length on pages 61 and 66 of the paper on irons and steels.

Another point raised by Mr. Moss had to do with the time factor *versus* thermal equilibrium. I am not certain that I understand exactly

Mr. French. what he means by the thermal equilibrium, but both the papers presented and the discussion have thoroughly emphasized the importance of the time factor. In other words, there is no doubt that the time factor is important and that it is distinct from what I understand Mr. Moss to mean by thermal equilibrium.

I might in that connection repeat a very short item appearing on page 72, which is quoted directly from a very valuable report by Robin, as follows:

> "The properties of steel, so far as the dynamic and static effects are concerned, vary in totally different ways according to the temperature and according to the nature of the steels. The correlation of these effects at the normal temperature in the case of certain steels appears, therefore, to be due purely to coincidence."

I think that the work of Robin will possibly clear up this question with respect to thermal equilibrium and the time element.

Everyone must agree with Mr. Fahrenwald that the time factor is of great importance in any discussion of the high-temperature properties of metals and this has been emphasized in the paper on irons and steels. However, Mr. Fahrenwald is too optimistic and not in agreement with any of the other speakers in stating that "Much of the information that has been hoped for and suggested by the various authors of these papers has already been worked out and has been available for some years to the trade." It is not quite consistent with his later statement that "The problem of the application of metals and alloys at high temperatures is far more complicated and difficult than is ordinarily supposed."

Another subject which has been touched upon in the discussion is cast metals including so-called heat-resisting alloys but no one has mentioned or at least emphasized the importance of foundry practice in the production of these alloys.

We have recently tested some of the nickel-chromium-iron alloys and the uniformity of the results obtained from ostensibly the same lot of material has not been at all satisfactory. If I remember correctly, in one case at moderate temperatures, values of 75,000 lb. per sq. in. tensile strength were obtained, and the duplicate determination gave something like 50,000 lb. There were no visible flaws in the specimen to account for such a difference and the cause was not apparent offhand. This question of uniformity is of prime importance from several angles including the interpretation of test data. Numerical values given should not be used unless there is sufficient evidence that the stated properties can be uniformly produced in any product. While this is primarily a metallurgical problem, it affects materially the engineering application of these materials.

A. E. WHITE (*Author's closure*).—During this discussion three things seem to stand out. **Mr. White.**

The first relates to the need for information regarding the modulus of elasticity. That strikes me as an outstanding need. Very little work has been done upon it to date.

The second is the need for the development of a short-time test which will enable one to duplicate with a short-time test the changes resulting from long-time exposures to the given condition. I think the contribution of Mr. Hoyt, in which he mentions the possibility of plotting the logarithm of the time against the square root of the load, is a very valuable suggestion and one which should be given very careful consideration.

The third matter is the need for a suitable classification of metals and alloys. What are some of the outstanding metals which seem to enable an alloy to maintain its properties at elevated temperatures and what are the particular characteristics of these metals? On looking over the charts which have been prepared from the nonferrous data, it is noted that in the main when nickel is added to copper one gets decidedly beneficial effects. We might, therefore, make a statement that nickel seems to be beneficial to the extent of enabling metals to maintain their properties at elevated temperatures. If we will look over the data in the field of the ferrous metals, we will find that chromium is of decided benefit. We may, therefore, say that chromium is a metal of decided value from this standpoint.

We can, then, go a step further and think of an alloy of nickel and chromium. This alloy, of course, constitutes the base for most of our present-day heat-resisting alloys. Then we can go just a step further and ask what the particular properties are in chromium and nickel which enable these metals, when alloyed or by themselves, to undergo less change at elevated temperatures than most other metals and alloys. That gets us into the field of basic fundamentals. It is a field on which much important work is being done to-day. Everyone will appreciate that when the splendid fundamental work which is being done with regard to atomic structure is better understood and appreciated and when it is carried a bit further we will then be able to convert that information into our engineering needs so as to perfect a metal or an alloy which will approximate at elevated temperatures the properties it has at atmospheric temperatures.

CLOSURE BY COMMITTEE ON ARRANGEMENTS.—Measurable progress should be made from this Symposium, which has directed attention to many phases of the application and testing of metals at high and low temperatures. Already, definite results have been ob- **Closure by Committee.**

Closure by Committee. tained, for it has (1) brought together widely scattered and important published information not in all cases readily accessible and likewise served to give a picture of the present state of our knowledge of the subject; (2) developed, through the general discussion, new data of value; and (3) focused attention upon the needs of industry and some of the most important problems to be solved separately or jointly by the metallurgist, chemist and engineer. It has, of course, been valuable in these respects and in promoting a widespread exchange of ideas, but of greater importance will be the future developments or what may be called the superstructure built upon the foundation of the Symposium.

As has been brought out in the Symposium, it is common knowledge that rather widely dissimilar results have been obtained by investigators in their tests of practically the same materials. This is not surprising, since they used different types of furnaces for heating the test pieces, different means of reading temperatures, various periods of time under heat, unlike speeds of loading, etc. It has become increasingly important that we know as accurately as possible the strengths of various engineering materials at elevated temperatures under approximate operating conditions. For this reason it is highly desirable that definite means be taken to determine the sources of error in the methods being used to-day and to determine upon a certain method or methods, which in the hands of investigators may be depended upon to give concordant results. Such methods when properly worked out and proved accurate, should be accepted as standard methods until superseded by other methods proved to be more accurate or advantageous.

In the belief that the time is now ripe for an organized and systematic effort along these lines, the Committee on Arrangements for the Symposium suggested the formation of a special committee under the joint auspices of the American Society of Mechanical Engineers and American Society for Testing Materials to foster and coordinate and possibly also to carry out service and laboratory investigations relating to the application and testing of metals at various temperatures.

[The above suggestion has met with the approval of the Executive Committee of the American Society for Testing Materials and the Council of the American Society of Mechanical Engineers, and plans are being made for the organization of a Joint Research Committee on the Properties of Metals at Extreme Temperatures.—ED.]

SYMPOSIUM ON CORROSION-RESISTANT, HEAT-RESISTANT AND ELECTRICAL-RESISTANCE ALLOYS

INTRODUCTION—WITH TABULATION OF MANUFACTURERS' DATA ON COMPOSITION AND PROPERTIES OF THE ALLOYS

The commercial development of steels offering an exceptional degree of permanence when subjected to a wide variety of deteriorating influences, has been largely confined to the past decade. Progress has been rapid, in fact so rapid that not only do new combinations of elements make their appearance each year, but also the original narrow field of application has so widened that these metals may now be found in practically every large manufacturing institution engaged in producing articles of engineering, commercial or domestic utility. This widespread use occasioned many comments in several of the Society's committees on the possibilities of standardization and led finally to an open discussion of the problem at the suggestion of Committee B-2 on Non-Ferrous Metals and Alloys. The opinion expressed at this time pointed to the undesirability of attempting standardization in a field of such rapid and diverse growth, but did indicate the need for dissemination of existing knowledge. A permanent record of such information, combined with the stimulating effect of the discussion that must result from the presentation of papers, appealed to this gathering as the most desirable action to be taken. Accordingly, the following committee was organized to act in an advisory capacity to the Committee on Papers, and arrange the present Symposium:

Jerome Strauss, *Chairman.*
P. A. E. Armstrong
W. H. Bassett
L. O. Hart
A. I. Krynitsky
P. D. Merica
H. M. Williams

The earlier discussions of the committee and also of the above-mentioned open meeting centered around the so-called "stainless steels" and their modifications and associated alloys. It was soon apparent, however, that these could not be effectively discussed without dealing also with the nickel-alloys, nickel-chromium-iron alloys and many copper-base metals, used not only under corrosive conditions but also for high-temperature service and as electrical resistors. Hence the title of this Symposium. A literal interpretation of this title makes possible, of course, the inclusion of practically all commercial metals; each, under some conditions of usage, is most permanent, resistant to the attack of its surroundings and capable of rendering continuous, satisfactory service. Covering such a wide field is obviously impossible, and consequently arrangements were confined largely to the presentation of data on those alloys having iron or nickel or copper as the predominating element and offering resistance to various dissimilar destructive agencies. Such alloys of other types as possess merit for specific applications would unquestionably be referred to in the course of the discussions and most satisfactorily covered in that way.

As an adjunct to the papers presented, the committee decided upon the preparation, in tabular form, of the properties of the various alloys produced in this country and falling within the scope of the title of this Symposium, as qualified above. The data desired were those in the possession of the manufacturers of the various metals; they were to be so assembled as to give to the prospective user a broad survey of the field from which he might, as a preliminary step, select several metals offering the greatest promise for a specific purpose. Further inquiry of the manufacturer, coupled with some form of comparative testing, would unquestionably be required in order to reach a final decision. Detailed consideration of many specialized applications was evidently impossible of inclusion in the proposed presentation. With this object in view, questionnaires were mailed to approximately sixty manufacturers. In the haste of selection some were included whose products would not properly fall within the scope of this survey or whose products had not reached a satisfactory stage of commercial development; others did not desire to have their materials listed; in general, however, the response to the committee's request, regardless of actual submission of data, was exceptionally good, replies having been obtained from well above 90 per cent of the original list.

The data accumulated is presented in Tables I, II and III. Attention is directed to the fact that the alloys listed may not be all that a given manufacturer is producing but only the principal ones applicable to the widest sphere of service. In many cases where the newer alloys are covered by patents, the compositions listed and

TABLE

Manufacturer	Designation of Material	Essential Nominal Chemical Composition, per cent										Form of Material	Uses for which Recommended			Typ
		C	Si	Mn	Ni	Cr	Fe	Cu	Zn	Sn	Al		Corrosion Resistance	Heat Resistance	Electrical Uses	
Allegheny Steel Co.	Ascoloy					14.0	[a]					Rods, bars, sheet, plates, tube, wire.	✓	✓	✓	
Atlas Steel Corp	Atlas Stainless	0.43				13.0	[a]					Billets, forgings, bars, rods, wire, C. D. rods and shapes.	✓			Cutlery, instrume turbine blades,
Carpenter Steel Co.	Carpenter Stainless	0.30				13.0	[a]					Bars, billets, forgings, wire.[d]	✓	✓	✓	Cutlery, instrumen turbine blades,
	Carpenter Rustless	0.30				20.0	[a]	1.0				Bars, billets, forgings, C. R. strip.	✓	✓	✓	Chemical equipme stirring rods, he
	30-per-cent Nickel Steel				30.0		69.0					Bars, billets, wire, C. R. strip.	✓		✓	Saddlery hardwar spark points.
	Corrosion Resistant Steel	0.45				9.5	[a]					Billets, bars, forgings, C. R. strip, C. D. rods.	✓	✓		Cutlery, measurin ments, valves, t
Crucible Steel Co.	No. 2600 Metal[e]												✓	✓		
	Rezistal No. 4[f]	From 0.15 to 0.70	From 1.25 to 3.25		From 22.0 to 36.0	From 5.5 to 27.5	From 65.0 to 45.0					Bars, rods, sheet and wire down to 0.005 in. diam.	✓	✓	✓	Safe parts, furnace rods in sea wat wire, spark poin welding cast iro ment.
	Rezistal No. 7[g]												✓	✓	✓	
	Rezistal No. 8[h]												✓	✓	✓	
Cyclops Steel Co.	No. 17 Metal	0.45	1.00	0.75	20.0	7.5	[a]					Bars, castings.[i]	✓	✓	✓	Pump rods, engine
Firth-Sterling Steel Co.	S-less Stainless Steel	0.30				13.0	[a]					Rolled products.	✓	✓	✓	Cutlery, cooking u gun parts, auto p and chemical eq
	S-less Stainless Iron	0.15				13.0	[a]					Rolled products.	✓	✓	✓	
Ludlum Steel Co.	Delhi Tough Iron	0.07	1.25			17.0	[a]					Bars, rods, wire, sheet, strip.	✓	✓	✓	Cooking utensils, ance units.
	Delhi Hard	1.20	1.50			17.0	[a]					Bars, rods, wire.	✓	✓		Balls, rollers and ra
	Silcrome	0.40	3.50			8.25	[a]					Bars, rods, wire, strip.		✓		Automotive and si
	Silcrome, Grade F	0.40	3.30			3.25	[a]					Bars, rods, sheet.	✓	✓		Automative and similar construct
The Midvale Co.	Stainless Steel (Low C)	0.35	0.35	0.50		15.0	[a]					Bars and forgings.	✓	✓		Cutlery, structural
	Stainless Steel (Med. C)	0.80	0.35	0.50		18.0	[a]					" "	✓	✓		Cutlery, edged tool
	Stainless Steel (High C)	1.00	0.35	0.50		23.0	[a]					" "	✓	✓		" " "
Vanadium Alloys Steel Co.	Stainless Steel	0.33				14.0	[a]					Forgings, bars, shapes.	✓	✓		Cutlery, valves.
The Calorizing Co.	Calite A	0.80			35.0	15.0	[a]					Castings.	✓	✓		Carbonizing boxes,
	Calite B	1.50			6.0	18.0	[a]					"		✓		Used only for beam temperatures.
Chrobaltic Tool Co.	Fire Armor				61.0	18.5	[a]				[a,r]	Castings, sheet.		✓		Carbonizing boxes; tainers, furnace p
General Alloys Co.	Q-Alloys				68.0	20.0	10.0					Castings, sheet, special rolled shapes.	✓	✓	✓	Furnace parts, carb retorts, oil-still pa brass rolls, valve
Michigan Steel Casting Co.	Misco Metal	0.50	1.50	0.50	25.0	15.0	57.5					Castings.		✓		Carbonizing boxes,
Driver-Harris Co.	Nichrome				60.0	12.0	[a]					Wire, strip, rod, sheet, forgings.	✓	✓	✓	Pickling machine p rheostats, heating
	Nichrome				66.0	16.0	[a]					Castings, forgings.[q]	✓	✓	✓	Dipping baskets, heavy resistors.
	Nichrome III				85.0	15.0						Wire, ribbon, sheet, forgings.	✓	✓	✓	High temperature e
	Nichrome IV				80.0	20.0						Forgings, wire, rod, strip.	✓	✓	✓	" "
	No. 193 Alloy				30.0	2.0	[a]					Wire, sheet, forgings.		✓	✓	Low temperature h rheostats.
	Cimet					25.0	[a]					Bars, rods, forgings, wire, sheet.[r]	✓	✓		
	Cimet					25.0	[a]					Castings.	✓	✓	•	Mine water pumps parts, mulling pla
	Advance				45.0			55.0				Wire, ribbon, sheet.		✓	✓	Rheostats, resistanc
	Manganin			12.0	4.0			84.0				Wire, sheet.			✓	Instrument shunts,
Cutler Steel Co. and Driver-Harris Co., licensees of Electro-Metallurgical Co.	Chrome Iron, Duraloy, Cimet					20.0[u]	[a]					Castings, bars, forgings, wire, tube, sheet.[v]	✓	✓		Annealing boxes, fur oil-cracking stills,
Haynes Stellite Co.	Stellite					[x]						Castings, forgings, small sheets.	✓	•		Dental and surgical gages, cutting too
The Duriron Co.	Duriron	0.60	14.25	0.35			84.6		P 0.16	S 0.04		Castings.	✓			Pumps, valves, pip acids and other co
Pacific Foundry Co. Bethlehem Foundry and Machine Co.	Corrosiron		13.5				85.5					Castings.	✓			Acid pans, pumps, pi valves, cocks.
Alloy Metal Wire Co.	Superior Nickel Chrome	0.20	0.80[a,e]	2.0	[a,d]	19.5	0.5					Wire and ribbon.	✓	✓	✓	Electrical heating de
	Peerless Nickel Chrome	0.10	0.25	2.0	[a,d]	16.5	3.0					" "		✓	✓	" "
	Premier Nickel Chrome			3.0	61.0	11.0	25.0					" "	✓	✓	✓	" "
	Silchrome	0.30	2.75	0.30		19.0	[a]		W 3.0			" "	✓	✓	✓	" "
	Acme Nickel Steel	0.10	0.75	0.18	30.5	1.75	[a]					" "	✓	✓	✓	Electrical resistance
	Pure Nickel				98.5+							" "	✓	✓		Hospital and laborat ports, anchors in W
	Manganese Nickel			4.7	[a]		0.5					Wire, ribbon, C. D. rods.				Spark points.
	Excelsior				45.2		0.3	53.4				Wire and ribbon.	✓		✓	Electrical measuring heating pads.
	Monel Metal	0.15	0.50	1.50	67.5		1.75	28.5				Wire and shapes.	✓			Wire cloth, pump par rope, needle valves
Electrical Alloy Co.	Karma				80.0	20.0						Wire, rod, ribbon, strip.		✓	✓	Furnace resistors, cha
	Elalco Rayo				85.0	15.0						" "		✓	✓	"
	Elalco Calido				60.0	16.0	[a]					" "	✓	✓	✓	Dipping baskets, resi toasters, etc.
	Elalco Comet				30.0	5.0	[a]					" "		✓	✓	Low priced heating u
	Elalco Pure Nickel				98.0+							" "	✓	✓	✓	Resistance pyromete leads.
	Elalco Manganese Nickel			2.0	97.0							" "	✓		✓	Lamp anchors, denta contacts.
	Elalco Magno			5.0	95.0							" "	✓	✓	✓	Spark points, pyrome iron.
	Elalco Ideal				45.0			55.0				" "			✓	Thermocouples, rheos
Hoskins Manufacturing Co.	Chromel A				80.0	20.0						Rod, wire, strip, flats, castings.		✓	✓	Electrical heating dev
	Chromel B				85.0	15.0						" " "		✓	✓	" "
	Chromel C				[a]	11.0	25.0					" " "	✓	✓	✓	" "
	Chromel D				26.0	8.0	66.0					" " "	....	....	✓	Rheostats.
	Chromel Alloy No. 502				25.0	20.0	55.0					Castings.	....	✓	....	Furnace parts, carbon
	Copel				45.0			55.0				Wire, ribbon.	✓	....	✓	Instrument constructi
	Alloy No. 484			1.5	[a]							Wire, ribbon.	....	....	✓	Spark points.
International Nickel Co.	Monel Metal	C+Si....1.0		2.0	67.0		2.0	28.0				Rod, sheet, forgings, strip, castings, tube, wire, screen, fabricated products.	✓	✓	✓	Pickling equipment, machinery, pump p trim, enameling po coils.
	Nickel (Commercially Pure)			0.25–5.0	94 - 99							As for Monel Metal.	✓	✓	✓	Large kitchen utensil points, jigs, pyrom furnace hearths.
American Brass Co.	Tobin Bronze							60.0	39.25	0.75		Sheets, rods, seamless tubes, pressings, castings.	✓			Pumps, shafts, plates water.
	Phosphor Bronze							95.8		4.0	P 0.2	Sheet, wire.	✓		✓	Screens for paper mak switch parts.
	Nickel Silver				18.0			55.0	27.0			Wire.			✓	Resistance wire.
	Low Brass							80.0	20.0			Sheet, rod, seamless tubes, wire.	✓			Where greater resist nary brass is requi
	Common High Brass							65.0	35.0			Sheet, rod, seamless tubes, wire, special shapes.	✓			Used generally where too severe.
	Ambrac Metal				20.0			75.0	5.0				✓			Laundry machinery, for handling sugar caustic solutions, e
American Metal Products Co.	Ampco Bronze						8.0	82.0			10.0	Ingots, castings, rod, sheet.	✓			Pickling equipment,
Aterite Co., Inc.	Aterite				10.0		2.0	65.0	23.0			Rods, bars, wire, sheets.	✓	✓		Valve parts, general
	Aterite				35.0–44.0		5.0–20.0	55.0–36.0	5.0–0			Castings.	✓	✓		" " "
Chapman Valve Manufacturing Co.	Davis Metal	C+Si....0.5		1.5	29.0		2.0	67.0				Castings.	✓	✓		Valves and fittings.
Chase Metal Works	Naval Brass							61.0	38.0	1.0		Rod, tube, wire, shapes.	✓			Gears, ship fastenin rods, welding rod.
	Admiralty Tubing							70.0	29.0	1.0		Tube.	✓			Condensers and he mild corrosives.
	Commercial Bronze Rod						Pb 0.75	86.0	12.75	0.5		Rod.	✓			
	18-per-cent Nickel Silver				18.0			66.0	16.0			Sheet.	✓			Silverware and orna
Curtis Bay Copper and Iron Works	Everbrite No. 90				35.0			60.0				Bars, forgings, sheet.	✓	✓		Valves for chemical sheets.
	Everbrite No. 92				35.0			58.0				Bars, forgings.	✓	✓		H. P. steam valves engine valves, ch
Dupont Engineering Co.	Everdur No. 50 Metal		4.5	1.0				94.5				Sheet, rod, forgings, wire, fabricated products. Castings.	✓ ✓			Equipment for ha salts.
Frontier Bronze Corp.	Titanium-Aluminum Bronze No. 1							90.0			10.0	Castings.	✓	✓		Valves, autoclaves,
	Titanium-Aluminum Bronze No. 5						1.0	89.0			10.0	Castings.	✓	✓		"
Scovill Manufacturing Co.	Naval Brass							60.0	39.25	0.75		Rods.	✓			Fittings subjected
	Admiralty Metal							70.0	29.0	1.0		Tube, sheet to 13 in. wide	✓			Condensers using s
	Admiralty Nickel				29.0			70.0		1.0		Tube, sheet to 6½ in. wide, wire.	✓			Laundry and resta densers, screens,
	Spring Oreide							92.0		8.0		Sheet to 6½ in. wide.	✓			
Standard Calorimeter Co.	Illium		0.5	1.5	63.0	21.0		8.0	Mo, 4.0	W, 2.0		Castings.	✓			Calorimeter bombs

E I.—PROPERTIES OF CORROSION-RESISTANT, HEAT-RESISTANT AND ELECTRICAL-RESISTANCE ALLOYS OF GENERAL MANUFACTURING INTEREST.

Typical Applications	Density, g. per cc.	Melting Point, deg. Cent.	Total Contraction, in. per ft.	Machining Qualities	Forging Qualities		Welding Qualities				Brazing Qualities		Cold Reduction possible without Annealing, per cent
					Optimum Temperature Range, deg. Cent.	General	Forge	Arc	Gas	Resistance	Spelter Solder	Silver Solder	
	7.65	1493^j		As of 0.45 C plain steel.	1065 – 1150			O.K.	^{b}		O.K.	O.K.	^{c}
uments, chemical equipment, valves, des, pump rods.		1500^k		Soft and tough.	1000 – 1100	Cool slowly after forging.		Poor	Poor	Poor	Poor	Poor	30
uments, chemical equipment, valves, des, spark plugs.	7.7	1430^k		Good; O.K. in screw machines.		As for standard H. S. steel.	Poor	O.K.	^{b}		O.K.	O.K.	30
ipment, pumps, valves, N. F. metal s, heating units^{as}.	7.7	1430^k		" " " "		" " " "	"	O.K.	^{b}		O.K.	O.K.	30
lware, pump shafts, resistance wire, s.	8.02			Soft; somewhat tough.		As for plain steels.	"	O.K.	^{b}		O.K.	O.K.	50
suring instruments, surgical instruves, turbine blades, ball bearings.				Good; O.K. in screw machines.		As for standard H. S. steel.	"	O.K.	^{b}		O.K.	O.K.	30
rnace parts, valves, shafts and pump water and mine water, resistance points, analytical weights, rods for st iron, rifle barrels, chemical equip-	7.76	1480^k	^{l}	Fair at moderate speed if annealed; tough.	1040	Do not forge above 1090.		O.K.	O.K.		Fair	Fair	
	7.76	1480^k	^{l}	" "	"			"	"		"	"	
	7.76	1480^k	^{l}	" "	"			"	"		"	"	
	7.76	1480^k	^{l}	" "	"			"	"		"	"	
ngine valves, resistance grids.	8.00		$\frac{13}{64}$	Tough; use lower speed than for mild steel.	1120			O.K.	^{b}	O.K.		O.K.	
king utensils, laboratory equipment, auto parts, golf club heads, electrical	7.75	1510^k		Readily machined.	925 – 1090	Preheat at 700° C.	No	O.K.	O.K.	O.K.	O.K.^{m}		^{n}
cal equipment.				Machines like soft steel.	not over 1040	" " "	"	"	"	"	"		^{n}
nsils, pump shafts, electrical resist- .	7.62	1510		Machines easily; for smooth finish may require changes in tool angles.		Forges well from 1180 down to black. Regulate initial temperature so as to finish about 700.			O.K.	O.K.		O.K.	
and races, cutlery, pump shafts.	7.63	1510		Machines well.	Black to 1150				"	"		"	
and similar valves.	7.60	1510		As most high-tensile steels.	" "	Rather rigid in forging.			"	"		"	
and similar valves; roofing and nstruction.	7.66	1510		Machines well.	" "				"	"		"	
uctural uses.				Tough; somewhat hard; machines like heat-treated nickel steel.	1175 – 1190	Like H. S. steel.		Poor	O.K.				
ged tools.				" "	" "	" "							
" "				" "	" "	" "		O.K.	O.K.				
lves.				Tough.	965 – 1090	Cool slowly after forging.		Poor	Poor	Poor	Poor	Poor	
boxes, retorts, hearth plates.	7.8	1480	$\frac{1}{4}$	As for 0.80 C tool steel.		Can be forged if C is reduced to 0.2 per cent.		O.K.^{o}					Not worked cold.
or beams supporting loads at elevated ures.	7.8	1480	$\frac{1}{4}$	Not machineable.		Not forgeable.		cannot weld					0
boxes; lead, salt and cyanide con- rnace parts.	8.0	1440	$\frac{1}{4}$	Tough; requires slow speed and feed.		Not forgeable.		O.K.	^{b}		O.K.	O.K.	Rolled with difficulty.
rts, carbonizing and annealing boxes, -still parts, glass rolls, dies and ladles, , valves, resistors, pyrometer tubes.				Machineable.		Forgeable.		O.K.	O.K.	O.K.			
boxes, furnace liners, conveyor links.	7.65		^{p}	Tough; machineable at low speed; can be drilled and tapped.									
chine parts, valves, annealing pots, heating units.	8.15	1300		Readily machineable.		Readily forgeable.		O.K.	^{b}	O.K.		O.K.	Hardens rapidly.
skets, carburizing boxes, retorts, stors.	8.06^{ac}	1260	$\frac{1}{4}$	" "				O.K.	^{b}				
rature electrical devices.	8.5	1320^k						O.K.	^{b}	O.K.		O.K.	Hardens rapidly.
" "	8.5			Readily machineable.		Readily forgeable.		O.K.	^{b}	O.K.		O.K.	"
rature heating devices, heavy duty	8.15			" "		" "		O.K.	^{b}	O.K.	O.K.	O.K.	
		^{t}		Machineable.		" "		O.K.	^{b}	O.K.			
pumps, pipes, fittings recuperator ling plates.	7.60	^{t}	$\frac{3}{16}$	"				O.K.	^{b}				
esistance spools, thermocouples.	8.9			Readily machineable.		Readily forgeable.		O.K.	^{b}	O.K.	O.K.	O.K.	
shunts, resistance standards.	8.15										O.K.	O.K.	
oxes, furnace parts, pyrometer tubes, g stills, chemical equipment.	7.6 – 7.8	1150 – 1450	$\frac{1}{4}$	In general, good; softer alloys tend to tear in threading.	800 – 1050	Forgeability decreases with increase in carbon.		^{w}	^{b}		O.K.	O.K.	
urgical instruments, valves, cutlery, ting tools.	8.2 – 9.3	1230 min.	$\frac{1}{4}$ – $\frac{5}{16}$	Not machineable; must be ground.	1000 – 1100	Forgeable alloys are low in W content.		O.K.	^{v}	O.K.	O.K.	Not possible	Not workable cold.
es, pipe, chemical equipment for other corrosive media.	7.00	1250	$\frac{3}{16}$	Hard and brittle, not machineable; must be ground, preferably wet.				Poor	^{b} ^{s}				
mps, pipe, anode plates, condensers, ks.	7.00	1290 – 1330	$\frac{1}{4}$	Hard; may be turned by sharp tools at low speed with light cuts; can cut coarse pitch round or square threads; easily ground.		Not forgeable.		O.K.^{ab}	O.K.^{ab}				
ating devices.	8.28												
" "	8.05	1530											
" "	8.26												
	7.5	1510											
istance units.	8.15	1510											
laboratory utensils, gas mantel supors in W lamps.	8.8	1455											
	8.8	1400											
asuring instruments, resistance coils, ds.	8.9	1200											
ump parts, furniture trimming, wire e valves.	8.96	1360		Readily machineable.				O.K.	O.K.		O.K.	O.K.	
tors, chains, stayrods, baskets.	8.4	1415		Hard and tough; grinding is best.				Fair	O.K.	O.K.	Difficult	O.K.	
"	8.43	1410		Hard and tough; machines with difficulty.				"	"	"	"	"	
ets, resistance units for irons, c.	8.15	1400						Fair	O.K.	O.K.	Fair	"^{af}	
eating units.	8.3	1480		Moderately hard; tough.				"	"	"	"	Fair	
yrometers, lamp anchors, filament	8.84	1450		Soft and tough; machines readily.				O.K.	O.K.	O.K.	O.K.	O.K.	
s, dental appliances, electrical	8.84	1430		" " " "				"	"	"	"	"	
pyrometers, welding rods for cast	8.8	1420		" " " "				"	"	"	"	"	
es, rheostats, radio apparatus.	8.9	1210		Tough; moderately soft; machines easily.				"	"	"	"	"	
ting devices.	8.40	1430^k		Machineable, but difficult.	1200^{ag}	Readily bent, forged and upset by hand; drop forging difficult.		O.K.^{ah}	O.K.	O.K.	Difficult		
" "	8.40	1430^k		" " "	"	" " "		"	"	"	"		
	8.26	1430^k		Somewhat easier to machine than "A" or "B".	"			"	"	"	"		
	8.26			" " " "	"			"	"	"	"		
, carbonizing boxes.	8.26	1430^k	$\frac{9}{32}$	" " " "				"	"	"	"		
nstruction, radio rheostats.	8.87												
oment, dyeing machinery, laundry pump parts, turbine blades, valve eling points, glass rolls, car-heater	8.80	1300 – 1350	$\frac{1}{4}$	Tough; to obtain best results, requires tool forms different from those used for cutting steel.	900 – 1150	Best results under hammer; use low-sulfur fuel.	No	O.K.	^{b}	O.K.	O.K.	O.K.	30 – 50^{aj}
utensils, dairy equipment, spark pyrometer protection tubes, rths.	8.84	1450	$\frac{1}{4}$	As for Monel Metal.	900 – 1200	As for Monel Metal.	No	O.K.	^{b}	O.K.	O.K.^{ai}	O.K.^{ai}	30 – 50^{ak}
, plates, bolts and rivets in sea	8.40	885		Machines easily.	750	Forges readily.		O.K.	O.K.	O.K.	O.K.	O.K.	30
per making, flat and helical springs, .	8.88	1050		Machines easily.		Can not be forged hot.		O.K.	O.K.	O.K.	O.K.	O.K.	50
e.	8.68	1055						O.K.	O.K.	O.K.	O.K.	O.K.	35
resistance to corrosion than ordis required.	8.67	1000		Machines easily.		Can be hot forged.		O.K.	O.K.	O.K.	O.K.	O.K.	50
where corrosive conditions are not	8.46	900		Machines easily.		Not suitable for hot forging.		O.K.	O.K.	O.K.	O.K.	O.K.	50
inery, salt air exposure, equipment sugar, tanning extracts, oils, dyes, ions, etc.	8.84	1175		Machines easily.		Can be hot forged.		O.K.	O.K.	O.K.	O.K.	O.K.	35
ment, chemical plant construction.	7.71	995	$\frac{1}{4}$	Tough; use high-speed steel tools.	870	Forges readily; hammer or press.		O.K.	O.K.	O.K.		O.K.	
eneral chemical equipment.	8.57	1305		About like rolled soft steel; O.K. in automatic screw machines.				O.K.	^{b}			^{al}	
" " "	8.46	1540		Readily machineable.									
ings.	8.75	1340											
stenings, propeller shafts, piston rod.	8.40	885		Fair; tough.		Forges readily; heat slowly.		O.K.	O.K.	Possible	O.K.	O.K.	25+
d heat exchangers subjected to es.	8.54	935		" "				"	"	"	"	"	75
	8.75	1000		Excellent.							"	"	30+
ornamental objects.	8.75	1110		Good.				O.K.	O.K.	O.K.	"	"	75
ical plants, pump parts, polished				Free machining; usual speed 100, sometimes 175 ft. per min.; requires tool form different than for steel.	1040 max.			O.K.	^{b}				
lves, oil distillation valves, gas , chemical plant equipment.				As above; also good grinding properties.	" "			O.K.	^{b}				
handling H_2SO_4, HCl and their	8.45	1050		Excellent.	750	Excellent.		O.K.	O.K.	O.K.	O.K.	O.K.	40 – 50
	8.15		$\frac{5}{32}$ $\frac{3}{16}$ ^{am}										
ves, shafts, gears.	7.45	980	$\frac{1}{4}$	Hard, tough; use plenty lubricant.	850	Similar to pure iron (except for lower temperature).					O.K.^{an}		
" "	7.45	980	$\frac{1}{4}$	" " " "	850	" " "					O.K.^{an}		
ed to attack of salt water.													
g sea water for cooling.													
staurant equipment, oil-still conns, food and beverage appliances.													50 – 60
													50 – 60^{ap}
													50 – 60^{aq}
bs, pump parts.	8.3	1300	$\frac{5}{16}$	Drills, turns threads like cast steel; tough; use dry tool, small clearance and back slope.^{ao}		Not forgeable.					Not possible		Not workable cold.

rrosion-Resistant, Heat-Resistant and Electrical-Resistance Alloys of General Manufacturing Interest.

Density, g. per cc.	Melting Point, deg. Cent.	Total Contraction, in. per ft.	Machining Qualities	Forging Qualities		Welding Qualities				Brazing Qualities		Cold Reduction possible without Annealing, per cent	
				Optimum Temperature Range, deg. Cent.	General	Forge	Arc	Gas	Resistance	Spelter Solder	Silver Solder		
7.65	1493[j]		As of 0.45 C plain steel.	1065 - 1150			O.K.	[b]		O.K.	O.K.	[c]	
	1500[k]		Soft and tough.	1000 - 1100	Cool slowly after forging.		Poor	Poor	Poor	Poor	Poor	30	
7.7	1430[k]		Good; O.K. in screw machines.		As for standard H. S. steel.	Poor	O.K.	[b]		O.K.	O.K.	30	
7.7	1430[k]		" " " "		" " " "	"	O.K.	[b]		O.K.	O.K.	30	
8.02			Soft; somewhat tough.		As for plain steels.	"	O.K.	[b]		O.K.	O.K.	50	
			Good; O.K. in screw machines.		As for standard H. S. steel.	"	O.K.	[b]		O.K.	O.K.	30	
7.76	1480[k]	[l]	Fair at moderate speed if annealed; tough.	1040	Do not forge above 1090.		O.K.	O.K.		Fair	Fair		
7.76	1480[k]	[l]	" "	"			"	"		"	"		
7.76	1480[k]	[l]	" "	"			"	"		"	"		
7.76	1480[k]	[l]	" "	"			"	"		"	"		
8.00		$\frac{13}{64}$	Tough; use lower speed than for mild steel.	1120			O.K.	[b]	O.K.		O.K.		
7.75	1510[k]		Readily machined.	925 - 1090	Preheat at 700° C.	No	O.K.	O.K.	O.K.	O.K.[m]		[n]	
			Machines like soft steel.	not over 1040	" " "		"	"	"	"		[n]	
7.62	1510		Machines easily; for smooth finish may require changes in tool angles.		Forges well from 1180 down to black. Regulate initial temperature so as to finish about 700.			O.K.	O.K.		O.K.		
7.63	1510		Machines well.	Black to 1150				"	"		"		I
7.60	1510		As most high-tensile steels.	" "	Rather rigid in forging.			"	"		"		
7.66	1510		Machines well.	" "				"	"		"		
			Tough; somewhat hard; machines like heat-treated nickel steel.	1175 - 1190	Like H. S. steel.		Poor	O.K.					
			" "	" "	" "								
			" "	" "	" "		O.K.	O.K.					
			Tough.	965 - 1090	Cool slowly after forging.		Poor	Poor	Poor	Poor	Poor		I
7.8	1480	$\frac{1}{4}$	As for 0.80 C tool steel.		Can be forged if C is reduced to 0.2 per cent.		O.K.[e]					Not worked cold.	U
7.8	1480	$\frac{1}{4}$	Not machineable.		Not forgeable.		cannot weld					0	
8.0	1440	$\frac{1}{4}$	Tough; requires slow speed and feed.		Not forgeable.		O.K.	[b]		O.K.	O.K.	Rolled with difficulty.	U
			Machineable.		Forgeable.		O.K.	O.K.	O.K.				
7.65		[p]	Tough; machineable at low speed; can be drilled and tapped.										D
8.15	1300		Readily machineable.		Readily forgeable.		O.K.	[b]	O.K.		O.K.	Hardens rapidly.	
8.06[ac]	1260	$\frac{1}{4}$	" "				O.K.	[b]					B
8.5	1320[k]						O.K.	[b]	O.K.		O.K.	Hardens rapidly.	K
8.5			Readily machineable.		Readily forgeable.		O.K.	[b]	O.K.		O.K.	"	
8.15			" "		" "		O.K.	[b]	O.K.	O.K.	O.K.		
	[t]		Machineable.		" "		O.K.	[b]	O.K.				N
7.60	[t]	$\frac{3}{16}$	"				O.K.	[b]					
8.9			Readily machineable.		Readily forgeable.		O.K.	[b]	O.K.	O.K.	O.K.		
8.15										O.K.	O.K.		Lo
.6 - 7.8	1150 - 1450	$\frac{1}{4}$	In general, good; softer alloys tend to tear in threading.	800 - 1050	Forgeability decreases with increase in carbon.		[u]	[b]		O.K.	O.K.		No
.2 - 9.3	1230 min.	$\frac{1}{4} - \frac{5}{16}$	Not machineable; must be ground.	1000 - 1100	Forgeable alloys are low in W content.		O.K.	[v]	O.K.	O.K.	Not possible	Not workable cold.	
7.00	1250	$\frac{3}{16}$	Hard and brittle, not machineable; must be ground, preferably wet.				Poor	[b] [s]					Sp
7.00	1290 - 1330	$\frac{1}{4}$	Hard; may be turned by sharp tools at low speed with light cuts; can cut coarse pitch round or square threads; easily ground.		Not forgeable.		O.K.[ab]	O.K.[ab]					Av
8.28													
8.05	1530												
8.26													
7.5	1510												
8.15	1510												
8.8	1455												
8.8	1400												
8.9	1200												
8.96	1360		Readily machineable.				O.K.	O.K.		O.K.	O.K.		
8.4	1415		Hard and tough; grinding is best.				Fair	O.K.	O.K.	Difficult	O.K.		He
8.43	1410		Hard and tough; machines with difficulty.				....	....	....	"	"		
8.15	1400						Fair	O.K.	O.K.	Fair	"[af]		
8.3	1480		Moderately hard; tough.				"	"	"	"	Fair		
8.84	1450		Soft and tough; machines readily.				O.K.	O.K.	O.K.	O.K.	O.K.		Co
8.84	1430		" " " "				"	"	"	"	"		
8.8	1420		" " " "				"	"	"	"	"		
8.9	1210		Tough; moderately soft; machines easily.				"	"	"	"	"		
8.40	1430[k]		Machineable, but difficult.	1200[ag]	Readily bent, forged and upset by hand; drop forging difficult.		O.K.[ah]	O.K.	O.K.	Difficult			
8.40	1430[k]		" " "	"	" " "		"	"	"	"			
8.26	1430[k]		Somewhat easier to machine than "A" or "B".	"			"	"	"	"			
8.26			" " " "	"			"	"	"	"			
8.26	1430[k]	$\frac{9}{32}$	" " " "				"	"	"	"			
8.87													
8.80	1300 - 1350	$\frac{1}{4}$	Tough; to obtain best results, requires tool forms different from those used for cutting steel.	900 - 1150	Best results under hammer; use low-sulfur fuel.	No	O.K.	[b]	O.K.	O.K.	O.K.	30 - 50[aj]	Lim sh
8.84	1450	$\frac{1}{4}$	As for Monel Metal.	900 - 1200	As for Monel Metal.	No	O.K.	[b]	O.K.	O.K.[ai]	O.K.[ai]	30 - 50[ak]	Lim sh
8.40	885		Machines easily.	750	Forges readily.		O.K.	O.K.	O.K.	O.K.	O.K.	30	Har ha
8.88	1050		Machines easily.	–	Can not be forged hot.		O.K.	O.K.	O.K.	O.K.	O.K.	50	Non
8.68	1055						O.K.	O.K.	O.K.	O.K.	O.K.	35	Har ha
8.67	1000		Machines easily.		Can be hot forged.		O.K.	O.K.	O.K.	O.K.	O.K.	50	Non
8.46	900		Machines easily.		Not suitable for hot forging.		O.K.	O.K.	O.K.	O.K.	O.K.	50	Hard ha
8.84	1175		Machines easily.		Can be hot forged.		O.K.	O.K.	O.K.	O.K.	O.K.	35	Non
7.71	995	$\frac{1}{4}$	Tough; use high-speed steel tools.	870	Forges readily; hammer or press.		O.K.	O.K.	O.K.		O.K.		
8.57	1305		About like rolled soft steel; O.K. in automatic screw machines.				O.K.	[b]			[al]		
8.46	1540		Readily machineable.										
8.75	1340												
8.40	885		Fair; tough.		Forges readily; heat slowly.		O.K.	O.K.	Possible	O.K.	O.K.	25+	
8.54	935		" "				"	"	"	"	"	75	
8.75	1000		Excellent.							"	"	30+	
8.75	1110		Good.				O.K.	O.K.	O.K.	"	"	75	Cold an
			Free machining; usual speed 100, sometimes 175 ft. per min.; requires tool form different than for steel.	1040 max.			O.K.	[b]					
			As above; also good grinding properties.	" "			O.K.	[b]					
8.45	1050		Excellent.	750	Excellent.		O.K.	O.K.	O.K.	O.K.	O.K.	40 - 50	
8.15		$\frac{5}{32}$ $\frac{3}{16}$[am]											
7.45	980	$\frac{1}{4}$	Hard, tough; use plenty lubricant.	850	Similar to pure iron (except for lower temperature).					O.K.[an]			
7.45	980	$\frac{1}{4}$	" " " "	850	" " "					O.K.[an]			
												50 - 60	
												50 - 60[ap]	
												50 - 60[aq]	
8.3	1300	$\frac{5}{16}$	Drills, turns threads like cast steel; tough; use dry tool, small clearance and back slope.[ao]		Not forgeable.					Not possible		Not workable cold.	Avoid cen

PLATE I.
PROC. AM. SOC. TESTING MATS
VOL. 24, PART II.
SYMPOSIUM ON CORROSION-RESISTANT, HEAT-RESISTANT AND ELECTRICAL-RESISTANCE ALLOYS.

ion h- ng,	Precautions to be Observed in Design of Parts and in Use of Metal	Designation of Material	Manufacturer
	For resistance to heat, not recommended above 800° C.	Ascoloy	Allegheny Steel Co.
	To develop maximum properties parts should be heat treated, ground and polished.	Atlas Stainless	Atlas Steel Corp.
	Machine free of surface defects, harden and temper and grind or otherwise remove hardening scale.	Carpenter Stainless	Carpenter Steel Co.
	Machine or clean free of scale. Cannot heat treat except to normalize or anneal.	Carpenter Rustless	
		30-per-cent Nickel Steel	
	Machine free of surface defects, harden and temper and grind or otherwise remove hardening scale.	Corrosion Resistant Steel	
		No. 2600 Metal[e]	Crucible Steel Co.
		Rezistal No. 4[f]	
		Rezistal No. 7[g]	
		Rezistal No. 8[h]	
		No. 17 Metal	Cyclops Steel Co.
	Forging at 1200° C. induces brittleness; same result from working below red heat; latter, like presence of oxide, increases corrodibility.	S-less Stainless Steel	Firth-Sterling Steel Co.
	Unlike S-less steel, heat treatment is not necessary to develop corrosion resistance. All scale and oxide must be removed.	S-less Stainless Iron	
		Delhi Tough Iron	Ludlum Steel Co.
	Must be heat treated for specific service; either hardened or annealed.	Delhi Hard	
		Silcrome	
		Silcrome, Grade F	
		Stainless Steel (Low C)	The Midvale Co.
		Stainless Steel (Med. C)	
		Stainless Steel (High C)	
	Parts should be heat-treated, ground and polished.	Stainless Steel	Vanadium Alloys Steel Co.
d	Use liberal fillets and uniform sections.	Calite A	The Calorizing Co.
	" " " " " "	Calite B	
	Uniform sections wherever possible.	Fire Armor	Chrobaltic Tool Co.
		Q-Alloys	General Alloys Co.
	Design for good foundry practice	Misco Metal	Michigan Steel Casting Co.
		Nichrome	Driver-Harris Co.
	Because of high strength at elevated temperatures, parts may be lighter than similar iron parts.	Nichrome	
	Keep sodium silicate away from heating elements.	Nichrome III	
	" " " " " " "	Nichrome IV	
		No. 193 Alloy	
	Neither polishing nor heat treatment required to secure stainless qualities.	Cimet	
		Cimet	
		Advance	
	Low thermal e.m.f. to copper. Must be artificially aged to avoid change of resistance and temperature coefficient with time.	Manganin	
	Not to be used in reducing atmosphere above 1100° C. Prolonged heating near 500° C. reduces shock resistance.	Chrome Iron, Duraloy, Cimet	Cutler Steel Co. and Driver-Harris Co., licensees of Electro-Metallurgical Co.
ble		Stellite	Haynes Stellite Co.
	Special precautions necessary in design of large plane areas. Use heavy rib at top of open vessels; steel inserts cast in place where required.	Duriron	The Duriron Co.
	Avoid large variations of section, sharp corners, and large flat planes; handle carefully and heat and cool slowly.	Corrosiron	Pacific Foundry Co. Bethlehem Foundry and Machine Co.
		Superior Nickel Chrome	Alloy Metal Wire Co.
		Peerless Nickel Chrome	
		Premier Nickel Chrome	
		Silchrome	
		Acme Nickel Steel	
		Pure Nickel	
		Manganese Nickel	
		Excelsior	
		Monel Metal	
	Heating in contact with silicates causes brittleness.	Karma	Electrical Alloy Co.
	" " " " " "	Elalco Rayo	
	" " " " " "	Elalco Calido	
		Elalco Comet	
	Contact with sulfur compounds at high temperature causes brittleness.	Elalco Pure Nickel	
		Elalco Manganese Nickel	
		Elalco Magno	
		Elalco Ideal	
		Chromel A	Hoskins Manufacturing Co
		Chromel B	
		Chromel C	
		Chromel D	
		Chromel Alloy No. 502	
		Copel	
		Alloy No. 484	
[aj]	Limitations on sizes and shapes of castings similar to steel, due to high shrinkage. Do not braze or solder when metal is under tension.	Monel Metal	International Nickel Co.
[ak]	Limitations on sizes and shapes of castings similar to steel, due to high shrinkage.	Nickel (Commercially Pure)	
	Hard material should not be used under corrosive conditions unless strains have been removed by light anneal or other treatment.	Tobin Bronze	American Brass Co.
	None.	Phosphor Bronze	
	Hard material should not be used under corrosive conditions unless strains have been removed by light anneal or other treatment.	Nickel Silver	
	None.	Low Brass	
	Hard material should not be used under corrosive conditions unless strains have been removed by light anneal or other treatment.	Common High Brass	
	None.	Ambrac Metal	
		Ampco Bronze	American Metal Products Co.
		Aterite	Aterite Co., Inc.
		Aterite	
		Davis Metal	Chapman Valve Manufacturing Co.
		Naval Brass	Chase Metal Works
		Admiralty Tubing	
		Commercial Bronze Rod	
	Cold worked articles to be annealed must be given low temperature anneal prior to final anneal to avoid fire cracking.	18-per-cent Nickel Silver	
		Everbrite No. 90	Curtis Bay Copper and Iron Works
		Everbrite No. 92	
		Everdur No. 50 Metal	Dupont Engineering Co.
		Titanium-Aluminum Bronze No. 1	Frontier Bronze Corp.
		Titanium-Aluminum Bronze No. 5	
		Naval Brass	Scovill Manufacturing Co.
		Admiralty Metal	
[p]		Admiralty Nickel	
[q]		Spring Oreide	
le	Avoid sudden change of section or bulky parts. Keep shafting 10 per cent oversize to compensate for poor central structure.	Illium	Standard Calorimeter Co.

NOTES

[a] Balance (including accidental impurities).
[b] Acetylene satisfactory.
[c] Erichsen Values (annealed).

$\frac{1}{64}$ in. Sheet	6 to 7
$\frac{1}{32}$ in. "	8 " 9
$\frac{1}{16}$ in. "	8 " 10

[d] Also cold rolled, tempered and tempered-and-polished strip.
[e] Lowest in alloying elements.
[f] Intermediate between 7 and 8.
[g] Highest in chromium.
[h] Highest in nickel.
[i] Data applies to bars only.
[j] ±15° C.
[k] Approximate.
[l] About as for cast iron.
[m] Recommend 50 Cu-50 Zn and flux of Borax. $FeCl_3$, HCl, $ZnCl_2$ at 870° C.
[n] Cold work increases corrodibility.
[o] Use calite "A" welding rod.
[p] $\frac{1}{4}$ in. in green sand molds.
$\frac{3}{16}$ in. in dry sand molds.
[q] Data applies to castings only.
[r] Data applies to sheet only.
[s] Also used for abrasion resistance.
[t] Varies widely according to composition.
[u] Minimum, usually 25 – 30 per cent.
[v] Properties apply to rolled products.
[w] Possible, but not as satisfactory as acetylene.
[x] Series of Co-Cr-W alloys.
[y] O.K. with acetylene if excess of gas is used
[z] Use duriron welding rod and great care in preheating and cooling.
[ab] Preheat entire casting thoroughly and cool slowly after welding. Use rod of same material.
[ac] Value is for castings; for forged material, density is 8.15.
[ad] Balance.
[ae] Total insolubles.
[af] Use borax as flux.
[ag] Rolling temperature.
[ah] In all welding, use flux of borax or fluorspar or fluorspar and iron oxide. Weld quickly to avoid boiling and consequent unsoundness.
[ai] Not embrittled by brazing.
[aj] Works practice; may be reduced 95 per cent. Erichsen on annealed sheet:

0.020-in. sheet	12.7
0.125-in. sheet	15.2

[ak] Same as [aj], but Erichsen slightly higher.
[al] Requires, for soldering, use of special metal and flux.
[am] According to thickness of section.
[an] Use $\frac{1}{4}$ spelter solder and $\frac{3}{4}$ borax.
[ao] Milling not recommended.
[ap] Erichsen values:

0.008-in. sheet, hard	2.3 to 2.9
0.012-in. sheet, hard	2.9
0.020-in. sheet, hard	3.8
0.012-in. sheet, soft	5.2
0.020-in. sheet, soft	5.6
0.010-in. sheet, annealed	8.5

[aq] Erichsen value, 0.0045-in. sheet, 8-in. hard, 0.9 to 1.2.
[ar] Balance carbon, silicon, manganese, aluminum, molybdenum.
[as] Also used for H. S. Steel hardening fixtures and Diesel engine combustion tubes.

Manufacturer	Designation of Material	Form of Material	Hardness			Tensile Properties, Room Temperature						Co
			Brinell	Scleroscope	Rockwell	Proportional Limit, lb. per sq. in.	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Modulus of Elasticity, 10⁶ lb. per sq. in.	Prop l lb. p
Allegheny Steel Co	Ascoloy	Wrought[a]	150 - 365			40 000 - 160 000		73 000 - 180 000	37 - 15	79 - 51	27.2	
Atlas Steel Corp	Atlas Stainless	Wrought[a]	163 - 477	24 - 70	58 C Max.	45 000 - 150 000		90 000 - 180 000	31 - 10	70.5 - 10.4		
Carpenter Steel Co	Carpenter Stainless	Wrought[a, c]	240 - 512	38 - 75			85 000 - 225 000	115 000 - 260 000	23 - 11	59 - 32	30.0	
	Carpenter Rustless	"[n]	200			50 000	68 000	100 000	22	50	30.0	
	30-per-cent Nickel Steel	"	160 - 200[p]			25 000	47 000	83 000	38	65		
	Corrosion-Resistant Steel	"[a, c]	225 - 540	36 - 73		55 000 - 130 000	80 000 - 260 000	110 000 - 290 000	23 - 9	65 - 27	30.0	
Crucible Steel Co	No. 2600 Metal	Wrought	156	26							27.0	
	Rezistal No. 4	"	up	up			62 000 - 90 000[r]	109 000 - 113 000	38 - 31	53 - 49	up	
	Rezistal No. 7	"	to	to							to	
	Rezistal No. 8	"	285[q]	60[q]			46 000 - 83 000[r]	91 000 - 129 000	33 - 16	41 - 28	30.0[q]	
Cyclops Steel Co	No. 17 Metal	Wrought	192	36		65 000	80 000	125 000	28	45	28.0	
Firth-Sterling Steel Co	S-less Stainless Steel	Wrought[a]	175 - 565				65 000 - 210 000	100 000 - 267 000	27 - 0	59 - 1	30.0+	
	S-less Stainless Iron	"										
Ludlum Steel Co	Delhi Tough Iron	Wrought[a]	163 - 170	24 - 26	85 - 87 B	45 000 - 50 000		77 000 - 85 000	50 - 25	67 - 14	26.7	46 000
	Delhi Hard	"[a]	207 - 600	27 - 80	88 B - 58 C	80 000 - 187 000		127 000 - 237 000	17 - 0	30 - 0	29.0	
	Silcrome	"[a]	197[w]	26[w]	92 B[w]	74 000 - 177 000	86 000 min.	124 000 - 212 000	25 - 2	53 - 4	29.5	70 000
	Silcrome, Grade F	"[a]	180[w]	27[w]	82 B[w]	72 000 - 74 000		106 000 - 118 000	44 - 8	53 - 16	29.5	
The Midvale Co	Stainless Steel (Low C)	Wrought[a, c]	230 - 485	40 - 70		66 000 min.	218 000 max.	117 000 - 241 000	22 - 6	61 - 11		
	Stainless Steel (Med. C)	"[a, c]	230 - 493	44 - 74		71 000 "	221 000 "	118 000 - 244 000	17 - 1	35 - 3		
	Stainless Steel (High C)	"										
Vanadium Alloys Steel Co	Stainless Steel	Wrought[a]	228 - 477			70 000 - 130 000		108 000 - 231 000	23 - 5	54 - 12		
The Calorizing Co	Calite A	Cast						60 000				
	Calite B	"						60 000				
Chrobaltic Tool Co	Fire Armor	Cast	210									
General Alloys Co	Q-Alloys	Cast										
Michigan Steel Casting Co	Misco Metal	Cast	85	27			47 000	63 000	5	17		
Driver-Harris Co	Nichrome	Wrought[a, f]	156 min.	15 min.			60 000	100 000	25	50		
	Nichrome	Cast	156 - 187	30			55 000	65 000	3	2		35
	Nichrome III	Wrought[a, g]					57 000	103 000	28	45		
	Nichrome IV	"[a, g]					63 000	112 000	26	55		
	No. 193 Alloy	"[a, f]					40 000	80 000	40	70		
	Cimet	"[a]	175 - 250				50 000 - 85 000	80 000 - 120 000	30 - 12			
	Cimet	Cast	200 - 600[a, h]			35 000		45 000	1	2		
	Advance	Wrought[a, f]				......	40 000	63 000	40	75		
	Manganin	"				......	......	......				
Cutler Steel Co. and Driver-Harris Co., licensees of Electro-Metallurgical Co	Chrome Iron, Duraloy, Cimet	Wrought	170 - 400[q, a, i]	17 - 60[q, a, i]		[q]	40 000 - 70 000	70 000 - 120 000	30 - 0	50 - 0		
Haynes Stellite Co	Stellite	Cast	470 - 650[a, h]	55 - 70[a, h]								
The Duriron Co	Duriron	Cast		50				10 000	0	0		
Pacific Foundry Co Bethlehem Foundry and Machine Co	Corrosiron	Cast		55								
Alloy Metal Wire Co	Superior Nickel Chrome	Wrought										
	Peerless Nickel Chrome	"										
	Premier Nickel Chrome	"										
	Silchrome	"										
	Acme Nickel Steel	"										
	Pure Nickel	"										
	Manganese Nickel	"										
	Excelsior	"										
	Monel Metal	"										
Electrical Alloy Co	Karma	Wrought					70 000[w]	115 000	25[a, f]	57		
	Elalco Rayo	"					......	110 000[w]				
	Elalco Calido	"					56 000[w]	100 000	28[a, f]	59		
	Elalco Comet	"					47 000	85 000	37[a, f]	69		
	Elalco Pure Nickel	"					20 000 - 120 000[p]	65 000 - 130 000	50 - 3		32.0	
	Elalco Manganese Nickel	"					......					
	Elalco Magno	"					......					
	Elalco Ideal	"					25 000 - 80 000[p]	70 000 - 100 000	50 - 0[a, f]			
Hoskins Manufacturing Co.	Chromel A	Wrought	241[a, k]					93000 - 119000[a, m]	52-25[ao, an]			
	Chromel B	"										
	Chromel C	"	196[a, l]					88000 - 97 000[a, m]	47-16[ao, an]			
	Chromel D	"										
	Chromel Alloy No. 502	Cast						30 000				
	Copel	Wrought						......				
	Alloy No. 484	"						......				
International Nickel Co	Monel Metal	Wrought	120 - 250	15 - 28[a, v]		30 000 - 60 000[a, r]	25 000 - 80 000	65 000 - 110 000[a, s]	50 - 20	70 - 50[a, r]	25.0	35 000 -
		Cast[a, q]	110 - 120				30 000 - 40 000	65 000 - 75 000	35 - 25			
	Nickel (Commercially Pure)	Wrought	80 - 120	12 - 20[a, v]			15 000 - 30 000	60 000 - 80 000[a, w]	50 - 20	70 - 50[a, r]	30.0	
		Cast[a, q]	80 - 100				20 000 - 30 000	50 000 - 60 000	30 - 20			
American Brass Co	Tobin Bronze	Wrought[b, t]		25 - 72[p]				54 000 - 90 000[p]	40 - 4[p]		11	
	Phosphor Bronze	"[b, t]	67 - 185[p]	18 - 67[p]				45 000 - 95 000[p]	50 - 5[p]		16	
	Nickel Silver	"[b, s]		27 - 69[p]				60 000 - 150 000[p]	40 - 1[p]			
	Low Brass	"[b, t]	53 - 165[p]	14 - 62[p]				43 000 - 85 000[p]	50 - 4[p]		13.7	
	Common High Brass	"[b, t]	52 - 153[p]	15 - 64[p]				45 000 - 85 000[p]	50 - 4[p]	60 - 45[p]	13.8	
	Ambrac Metal	"[b, t]	70 - 163[p]	18 - 62[p]				50 000 - 85 000[p]	35 - 5[p]	65 - 60[p]		
American Metal Products Co.	Ampco Bronze	Wrought and Cast		18 - 50			25 000 - 40 000	65 000 - 90 000	40 - 4			
Aterite Co., Inc	Aterite	Wrought		15 - 41[b, c]			40 000 - 110 000+[b, c]	53 000 - 163 000	59 - 1	62 - 17		
	Aterite	Cast					35 000 - 110 000	55 000 - 110 000	45 - 0.6	36 - 10		
Chapman Valve Manufacturing Co	Davis Metal	Cast	120				40 000	67 000			24.0	
Chase Metal Works	Naval Brass	Wrought	90 - 140		......		25 000 - 60 000	54 000 - 70 000	50 - 22	60 - 35		
	Admiralty Tubing	"			30 - 55[b, h] 23 - 25[b, i]			50 000 - 60 000	70 - 40			
	Commercial Bronze Rod	"	106		35[b, h] 5[b, i]			55 000 - 70 000	35 - 15			
	18-per-cent Nickel Silver	"[b, j]	158 - 197		50 - 78[b, h] 11 - 60[b, i]			57 000 - 86 000	50 - 2			
Curtis Bay Copper and Iron Works	Everbrite No. 90[b, q]	Wrought	130				40 000	70 000	30	50		
	Everbrite No. 92[b, q]	"	175				55 000	90 000	25	50		
Dupont Engineering Co	Everdur No. 50 Metal	Wrought	119	19 - 20			48 000 min.[b, c]	56 000 - 143 000	56 - 0	53 - 0		
		Cast					30 000	50 000	24	35		
Frontier Bronze Corp	Titanium-Aluminum Bronze No. 1	Cast	90 - 100			20 000	24 000	65 000 - 80 000	25 - 15	24 - 16		19 0
	Titanium-Aluminum Bronze No. 5	"	90 - 100			20 000	24 000	65 000 - 80 000	25 - 15	24 - 16		19 0
Scovill Manufacturing Co.	Naval Brass	Wrought		17			35 000	65 000	42	44		
	Admiralty Metal	"					35 000 - 40 000[b, n]	57 000 - 60 000	50 - 46	60 - 58		
	Admiralty Nickel	"		17 - 37[b, e]				69 000 - 131 000	31 - 0[b, o]	31 - 0		
	Spring Oreide	"		14 - 42[b, e]	11 - 67[b, e, b, i]			94 000 - 103 000[b, p]	1[b, p]			
Standard Calorimeter Co	Illium	Cast	130	27				85 000	5	2		

TA

Compression Properties, Room Temperature			Torsional Properties, Room Temperature				Impact, Room Temperature		Endurance Limit, lb. per sq. in.								
										At 20° C.				At 100° C.			
Proportional Limit, lb. per sq. in.	Yield Point, lb. per sq. in.	Compressive Strength, lb. per sq. in.	Shear Strength at Proportional Limit, lb. per sq. in.	Shear Strength at Maximum Load, lb. per sq. in.	Angle of Twist at Rupture, deg. per in. of length	Modulus of Rigidity. 10⁶ lb. per sq. in.	Izod, ft-lb.	Charpy, ft-lb.		Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reductio of Area, per cent
								190 – 550[b]	35 000[e]	60 000	82 000	46	71				
									......	......	......	......	......	......	......	......	......
									40 000[o]	32 500[bu bw]	104 500	18	33	32 000	99 500	16	33
							......			93 800	123 000	29	36	88 800	115 000	27.5	42
							......			41 000	102 000	39	51				
							52 – 53[s]			43 000	100 000	33	29				
							......			......	......	......	......				
							70 – 75		53 000[t]								
46 000 – 49 000			29 000 – 31 000	48 000 – 51 000			48 – 86[u]										
70 000 – 152 000		209 000 max.	47 000 – 112 000	94 000 – 157 000			0 – 42[x]										
										[bv]40 000[bw]	65 000	0.5	0.5	38 000	60 500	0.5	1
										[bv]35 000[bw]	62 500	0	0	33 500	60 000	0	0
										46 000	60 000	1.2	2.9				
......		......								60 000	100 000	25	50		......		
35 000		211 000								......					......		
										......					98 000	25	50
										......					110 000	27	50
										......							
										83 000	117 000			76 000	115 000		
										......	45 000			......	44 000		
										......				......			
										......				......			
									25 000[aj]						115 000	10	
		70 000															
		68 000															
35 000 – 45 000	60 000 – 70 000	No fracture	20 000 – 30 000	55 000 – 65 000		9.5	No fracture	100 – 200	35 000[at]	44 000[aw]	90 000	47	69	37 000	85 000	45	67
						10.0			29 000[ax]	25 000[ay]	81 000	54	72	24 000	82 000	54	71
		No fracture	30 000[bd]	65 000					24 700[be]								
		No fracture	18 000	55 000					17 600[bf]								
										39 000[bg]	66 000	18	15	39 000	62 000	14	12
										51 000[bg]	102 000	26	44	51 000	98 000	25	43
											73 000	44	51				
											......						
19 000									35 000[bm]								
19 000									35 000[bm]								
									[bw]	60 000[bz]	94 000	12	38	60 000	89 000	10	38
											......	......	......	......	......	......	......

Table II.—Mechanical Properties of Corrosion-Resistant, Heat-Resistant and Electrical-Resistanc

At 20° C.			At 100° C.				At 200° C.				At 300° C.				At 400° C.		
Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent
82 000	46	71					54 000[d]	76 000	44	69	48 000[e]	70 000	37	72	43 000[f]	61 000	35
......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
104 500	18	33	32 000	99 500	16	33	31 000	92 000	15	33	28 000	97 500	14	29	25 000	103 500	13
123 000	29	36	88 800	115 000	27.5	42	83 200	113 900	30	40	75 200	101 500	32	46	84 000	108 000	21
102 000	39	51													41 000[f]	91 000	30
100 000	33	29													39 000[f]	88 000	31
......	......	......													......	......	......
							87-85[e] [d]				76 - 72[e]				79 - 66[f]		
65 000	0.5	0.5	38 000	60 500	0.5	1	35 000	55 500	1	2.5	32 500	55 000	1.2	2	30 000	54 000	1.5
62 500	0	0	33 500	60 000	0	0	31 000	57 000	0	0	28 000	53 500	0	0	25 500	50 000	0
60 000	1.2	2.9															
100 000	25	50		......				94 000	19	58						91 000	
				......								49 000	[a] [e]	[a] [e]		49 000	[a] [e]
				98 000	25	50		98 000	25	45		98 000	23			94 000	22
				110 000	27	50		103 000	23	43		103 000	21	40		96 000	20
117 000			76 000	115 000			69 000	113 000			64 000	112 000			58 000	109 000	
45 000			......	44 000				44 000			......	43 000			......	42 000	
			......					52 000	40		......				......	49 000	
			......					......	......		......				......	......	
				115 000	10			114 000	10			113 000	10			108 000	10
																Stronger at e	
90 000	47	69	37 000	85 000	45	67	34 000	83 000	43	65	32 000	82 000	42	64	31 000	79 000	39
81 000	54	72	24 000	82 000	54	71	23 000	83 000	54	70	22 000	83 000	54	69	21 000	82 000	54
66 000	18	15	39 000	62 000	14	12	37 000	56 000	11	10	36 000	55 000	12	10	36 000	52 000	16
102 000	26	44	51 000	98 000	25	43	50 000	94 000	25	42	50 000	90 000	24	41	51 000	85 000	23
73 000	44	51										60 000[e]	33	67		36 000[bk]	26
......												......				......	
94 000	12	38	60 000	89 000	10	38	60 000	83 000	8	38	60 000	80 000	6	26	49 000	73 000	7
......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......

TANCE ALLOYS.

Tensile Properties at Elevated Temperatures

		At 500° C.				At 600° C.				At 700° C.				At 800° C.				At 9	
ion ., nt	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.
	70	30 000[g]	45 000	39	79	18 000[h]	26 000	44	89	12 000[i]	16 000	40	91	5 500[j]	10 500	40	92		8 800[k]
	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
	26	22 500	82 000	13	38	20 000	60 000	14	51	12 500	37 500	27	71	5 000	12 000	38	88	3 000	8 000
	37	70 000	100 000	24	30														
	47																		
	43																		
	......																		
		80 - 72[g]				67 - 37[h]	......				......				......				
							......				......				......				
							72 200[y]				54 600[z]				16 600[ab]				
							......				......				......				
	1.5	27 500	53 500	1.8	2	25 000	52 500	2	3	22 500	49 000	2.5	3.5	20 000	45 500	2	4	13 500	31 000
	0	22 500	47 500	0	0	20 000	45 000	0	0	16 500	38 000	0.2	0.2	13 500	31 000	0.5	0.5	10 000	21 500
											44 000[ad]	5	17						
	56		......				50 000	7	17		......				32 000	15	43		......
	[ae]		......				44 000	[ae]	[ae]		......				30 000	2	4		18 500
			79 000	20	50		60 000	13	30		32 000	18	35		12 000	27	60		12 000
	50		73 000	9	9		59 000	11	13		35 000	25	37		12 000	30	48		10 000
			97 000				53 000				18 000				9 000				5 000
			37 000				20 000				7 000				3 500				
			43 000				25 000												
			......				......												
			97 000	11			53 000	15			18 500	32			9 000	52			5 000
er at elevated temperature than at room temperature. At red heat and above, it will stand considerable abuse.																			
	63	30 000	68 000	34	40	20 000	31 000	8	11	12 000	18 000	9	10	7 000	12 000	15	18	4 000	8 000
	68	20 000	64 000	54	71	20 000	49 000	54	74	15 000	36 000	52	78	10 000	19 000	43	40	6 000	14 000
	14	36 000	50 000	17	15														
	38	52 000	81 000	20	32	44 000	72 000	16	24	28 000	55 000	12	16						
	69		14 500[bl]	18	71														
			......																
	13	36 000	57 000	6	11	20 000	40 000	7	10	9 000	25 000	8	10						
	......	......	......	......	......	......	......	......	......	......	......	......	......						

Tensile Properties at Elevated Temperatures

At 500° C.				At 600° C.				At 700° C.				At 800° C.				At 900° C.			
Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Redu of per
30 000[g]	45 000	39	79	18 000[h]	26 000	44	89	12 000[i]	16 000	40	91	5 500[j]	10 500	40	92		8 800[k]	52	5
......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	
22 500	82 000	13	38	20 000	60 000	14	51	12 500	37 500	27	71	5 000	12 000	38	88	3 000	8 000	55	9
70 000	100 000	24	30																
80 - 72[g]				67 - 37[h]	......				......				......						
					......				......				......						
					72 200[y]				54 600[z]				16 600[ab]						
					......				......				......						
27 500	53 500	1.8	2	25 000	52 500	2	3	22 500	49 000	2.5	3.5	20 000	45 500	2	4	13 500	31 000	6.5	14
22 500	47 500	0	0	20 000	45 000	0	0	16 500	38 000	0.2	0.2	13 500	31 000	0.5	0.5	10 000	21 500	1	0.
									44 000[ad]	5	17								
	......				50 000	7	17		......				32 000	15	43		......		
	......				44 000	[ae]	[ae]		......				30 000	2	4		18 500	7	9
	79 000	20	50		60 000	13	30		32 000	18	35		12 000	27	60		12 000	20	50
	73 000	9	9		59 000	11	13		35 000	25	37		12 000	30	48		10 000	35	60
	97 000				53 000				18 000				9 000				5 000		
	37 000				20 000				7 000				3 500						
	43 000				25 000														
	.....				......														
	97 000	11			53 000	15			18 500	32			9 000	52			5 000	70	

temperature than at room temperature. At red heat and above, it will stand considerable abuse.

30 000	68 000	34	40	20 000	31 000	8	11	12 000	18 000	9	10	7 000	12 000	15	18	4 000	8 000	19	26
20 000	64 000	54	71	20 000	49 000	54	74	15 000	36 000	52	78	10 000	19 000	43	40	6 000	14 000	36	35
36 000	50 000	17	15																
52 000	81 000	20	32	44 000	72 000	16	24	28 000	55 000	12	16								
	14 500[b l]	18	71																
	......																		
36 000	57 000	6	11	20 000	40 000	7	10	9 000	25 000	8	10								
......	......	......	......	......	......	......	......	......	......	......	......								

PLATE II.
PROC. AM. SOC. TESTING MATS.
VOL. 24, PART II.

SYMPOSIUM ON CORROSION-RESISTANT HEAT-RESISTANT AND ELECTRICAL-RESISTANCE ALLOYS

	At 1000° C.				At 1100° C.					
Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Designation of Material	Manufacturer
57		7 800[l]	60	65		4 300[m]	64	93	Ascoloy	Allegheny Steel Co.
									Atlas Stainless	Atlas Steel Corp.
......	......	......	......	......					Carpenter Stainless	Carpenter Steel Co.
90	1 000	5 500	70	93					Carpenter Rustless	
									30-per-cent Nickel Steel	
									Corrosion-Resistant Steel	
									No. 2600 Metal	Crucible Steel Co.
									Rezistal No. 4	
									Rezistal No. 7	
									Rezistal No. 8	
									No. 17 Metal	Cyclops Steel Co.
									S-less Stainless Steel	Firth-Sterling Steel Co.
									S-less Stainless Iron	
		......							Delhi Tough Iron	Ludlum Steel Co.
		......							Delhi Hard	
		8 700[l]							Silcrome	
		......							Silcrome, Grade F	
									Stainless Steel (Low C)	The Midvale Co.
									Stainless Steel (Med. C)	
									Stainless Steel (High C)	
									Stainless Steel	Vanadium Alloys Steel Co.
14	6 500	16 000	10	26	5 500	12 500	13	30	Calite A	The Calorizing Co.
0.7	6 000	12 000	1.5	1	3 500	7 500	3.5	1.7	Calite B	
									Fire Armor	Chrobaltic Tool Co.
	21 000[br]	27 000	3.2	3.3					Q-Alloys	General Alloys Co.
									Misco Metal	Michigan Steel Casting Co.
		......				......			Nichrome	—
9		11 700	15	16		6 400	20	18	Nichrome	Driver-Harris Co.
50		8 000	25	37					Nichrome III	
60		10 000	42	54					Nichrome IV	
									No. 193 Alloy	
		3 000							Cimet	
									Cimet	
									Advance	
									Manganin	
		2 500	85						Chrome Iron, Duraloy, Cimet	Cutler Steel Co. and Driver-Harris Co., licensees of Electro-Metallurgical Co.
									Stellite	Haynes Stellite Co.
									Duriron	The Duriron Co.
									Corrosiron	Pacific Foundry Co. Bethlehem Foundry and Machine Co.
									Superior Nickel Chrome	Alloy Metal Wire Co.
									Peerless Nickel Chrome	
									Premier Nickel Chrome	
									Silchrome	
									Acme Nickel Steel	
									Pure Nickel	
									Manganese Nickel	
									Excelsior	
									Monel Metal	
									Karma	Electrical Alloy Co.
									Elalco Rayo	
									Elalco Calido	
									Elalco Comet	
									Elalco Pure Nickel	
									Elalco Manganese Nickel	
									Elalco Magno	
									Elalco Ideal	
						5 000[m]	19[an]		Chromel A	Hoskins Manufacturing Co.
									Chromel B	
						4 100[m]	15[an]		Chromel C	
									Chromel D	
									Chromel Alloy No. 502	
									Copel	
									Alloy No. 484	
26	2 000	5 000	21	29	1 000	4 000	22	22	Monel Metal	International Nickel Co.
35	4 000	11 000	40	46	3 500	8 000	78	99	Nickel (Commercially Pure)	
					3 000[az]	6 000	95	99		
									Tobin Bronze	American Brass Co.
									Phosphor Bronze	
									Nickel Silver	
									Low Brass	
									Common High Brass	
									Ambrac Metal	
									Ampco Bronze	American Metal Products Co.
									Aterite	Aterite Co., Inc.
									Aterite	
									Davis Metal	Chapman Valve Manufacturing Co.
									Naval Brass	Chase Metal Works
									Admiralty Tubing	
									Commercial Bronze Rod	
									18-per-cent Nickel Silver	
									Everbrite No. 90	Curtis Bay Copper and Iron Works
									Everbrite No. 92	
									Everdur No. 50 Metal	Dupont Engineering Co.
									Titanium-Aluminum Bronze No. 1	Frontier Bronze Corp.
									Titanium-Aluminum Bronze No. 5	
									Naval Brass	Scovill Manufacturing Co.
									Admiralty Metal	
									Admiralty Nickel	
									Spring Oreide	
									Illium	Standard Calorimeter Co.

NOTES

[a] Variations of properties, where given, are according to condition of thermal treatment.

[b] Variation between annealed and "as rolled" metal.

[c] 33 × 10^6 revolutions on Farmer machine at 1200 r.p.m. without failure.

[d] This test at 300° F.

[e] " " " 500° F.

[f] " " " 700° F.

[g] " " " 900° F.

[h] " " " 1100° F.

[i] " " " 1300° F.

[j] " " " 1500° F.

[k] " " " 1700° F.

[l] " " " 1800° F.

[m] " " " 2000° F.

[n] Physical properties vary slightly according to annealing treatment.

[o] Upton-Lewis machine.

[p] According to amount of cold working.

[q] Varies with heat treatment, cold working and composition.

[r] Variation due to heat treatment of 0.40 to 0.60 per cent carbon material.

Wires are made with tensile strength up to 150,000 lb. per sq. in.

[s] 1 × 5-mm. notch on 10-mm. bar.

[t] Farmer machine.

[u] Unnotched bar, 73 to 92.

[v] For this steel first value in this and succeeding columns is Rockwell and second is notched Izod.

[w] Annealed.

[x] Unnotched specimens.

[y] This test at 1200° F.

[z] " " " 1400° F.

[ab] " " " 1600° F.

[ac] Variations in heat treatment, excluding annealing.

[ad] This test at 1250° F.

[ae] Slight.

[af] Elongation taken in 8 in.

[ag] " " " 4 in.

[ah] According to composition.

[ai] For castings 170 – 600 Brinell, 25 – 80 Scleroscope.

[aj] Farmer machine, 0.4 in. diameter by 13.0 in. specimen stood 5 × 10^6 revolutions.

[ak] As rolled; 124 as cast.

[al] " " ; 105 " "

[am] Variations between hot rolled rod and wire.

[an] Elongation in 6 in.

[ao] " " $1\frac{1}{2}$ in.

[ap] Same for cast Chromel "A" and "C".

[aq] Properties vary with form of product, degree of cold work and annealing treatment.

[ar] Refers to rods only.

[as] Cold-drawn wire 120,000 – 140,000 lb. per sq. in. tensile strength and 1 – 2 per cent elongation.

[at] Rotating beam tests, 100 × 10^6 revolutions to rupture.

[au] Pulling speed, 0.05 in. per minute to yield point, then 1.18 in. per minute to rupture.

[av] Excluding cold-rolled and cold-drawn products.

[aw] Cold-drawn wire 110,000 – 130,000 lb. per sq. in. tensile strength and 1 – 2 per cent elongation.

[ax] Limiting fatigue range on nickel of 73,000 lb. per sq. in. tensile strength by deflection and rise-of-temperature methods.

[ay] Pulling speed, 0.05 in. per minute to yield point, then 1.12 in. per minute to rupture.

[az] This test at 1200° C.

[bc] Varies according to amount of cold working and degree of annealing.

[bd] On round bars, one number hard.

[be] 5.6 × 10^6 revolutions to rupture; type of test not given.

[bf] 3.6 × 10^6 " " " " " " "

[bg] All high temperature tests on this metal record proportional limit.

[bh] $\frac{1}{16}$ in. Ball, 60 kg., C scale.

[bi] " 100 kg., "

[bj] Tests on this metal are variations on 0.080-in. sheet from soft to 4 numbers hard.

[bk] This test at 750° F.

[bl] " " " 1000° F.

[bm] White-Souther machine, 10 × 10^6 cycles for failure.

[bn] These tests on material annealed at 450° C.

[bo] Elongation taken in 1 in.

[bp] 0.0045-in. sheet, 8 numbers hard.

[bq] With the exception of high temperature tests, data on this material are average minimum values.

[br] This test at 1750° F.

[bs] Physical properties apply to wire only.

[bt] Physical properties apply to sheet only.

[bu] Tests on material quenched from 1000° C. Data gives Proportional Limit in Yield Point column.

[bv] Proportional limit of this material given in Yield Point column:

Values at 1150° C. are:

Material	P. L.	T. S.	E.	R.
Calite A	5000	11 000	15	31
" B	2 500	5 500	4.2	2

[bw] Rate of loading for this material approximately 0.05 in. per min.

[bx] Proportional limit of this material given in Yield Point column.

Manufacturer	Designation of Material	Form of Material	Thermal Conductivity Room Temperature C. G. S. Unit	Mean Coefficient of Thermal Expansion 0 - 100° C.	Specific Electrical Resistance, ohms per circ. mil. ft.										
					At 20° C.	At 100° C.	At 200° C.	At 300° C.	At 400° C.	At 500° C.	At 600° C.	At 700° C.	At 800° C.	At 900° C.	At 1000° C.
Allegheny Steel Co.	Ascoloy	Wrought	a		570 - 600										900^{b}
Atlas Steel Corp.	Atlas Stainless	Wrought^{bq}													
Carpenter Steel Co.	Carpenter Stain'ess	Wrought		......	......	......	......	......	......	......	......	......	......	......	......
	Carpenter Rustless	"		f	381	428	487	546	604	663	722	770	792	817	
	30-per-cent Nickel Steel	"			525										
	Corrosion-Resistant Steel	"													
Crucible Steel Co.	No. 2600 Metal	Wrought		......	......	......									
	Rezistal No. 4	"		g	560^{h}	i									
	Rezistal No. 7	"		g											
	Rezistal No. 8	"		g											
Cyclops Steel Co.	No. 17 Metal	Wrought		0.0000168	525	v									
Firth-Sterling Steel Co.	S-less Stainless Steel	Wrought	0.0445	0.0000109^{z}	316										
	S-less Stainless Iron	"													
Ludlum Steel Co.	Delhi Tough Iron	Wrought			535										
	Delhi Hard	"			540										
	Silcrome	"			457										
	Silcrome, Grade F	"													
The Midvale Co.	Stainless Steel (Low C)	Wrought													
	Stainless Steel (Med. C)	"													
	Stainless Steel (High C)	"													
Vanadium Alloys Steel Co.	Stainless Steel	Wrought													
The Calorizing Co.	Calite A	Cast		a c											
	Calite B	"		a e											
Chrobaltic Tool Co.	Fire Armor	Cast		0.000014^{ad}											
General Alloys Co.	Q-Alloys	Cast													
Michigan Steel Casting Co.	Misco Metal	Cast													
Driver-Harris Co.	Nichrome	Wrought	0.033	0.0000122	660	675	694	710	721	730	735	740	744	752	763
	Nichrome	Cast	0.033	0.0000122	720	740	760	777	790	800	803	808	815	824	836
	Nichrome III	Wrought	0.033	0.0000132	540	546	554	562	570	576	576	577	584	590	600
	Nichrome IV	"	0.033	0.0000132	620	631	637	643	650	855	653	650	655	658	665
	No. 193 Alloy	"	......		550	585	617	637	667	689	719	730	755	791	
	Cimet	"	0.082^{ae}	ah	104										270^{b}
	Cimet	Cast	......	0.0000153^{ad}											
	Advance	Wrought	......		294	Tempera	ture coef	ficient =	± 0.000	01 from 0	- 350° C				
	Manganin	"	......		270^{ai}	"		" =	± 0.000	005 " 1	5 - 45° C.				
Cutler Steel Co. and Driver-Harris Co., licensees of Electro-Metallurgical Co.	Chrome Iron, Duraloy, Cimet	Wrought and Cast	a j	0.0000119^{ad}	108 - 277^{ak}										271 - 343^{ak} ^{b}
Haynes Stellite Co.	Stellite	Cast		0.0000136^{am}	470										
The Duriron Co.	Duriron	Cast	0.125	0.0000292	429^{an}	568									
Pacific Foundry Co. Bethlehem Foundry and Machine Co.	Corrosiron	Cast													
Alloy Metal Wire Co.	Superior Nickel Chrome	Wrought			620	Mean te	mperatur	e coeffici	ent (20 -	1000° C.)	0.00011				
	Peerless Nickel Chrome	"			575	Temper	ature coe	fficient	0.00018						
	Premier Nickel Chrome	"			655	Mean t	emperatu	re coeffic	ient (20 -	1000° C.)	0.00018				
	Silchrome	"			655	Temper	ature coe	fficient	0.00042						
	Acme Nickel Steel	"			525	"		"	0.0004						
	Pure Nickel	"			64	"		"	0 0023						
	Manganese Nickel	"			120	"		"	0 002						
	Excelsior	"			296	"		"	nil						
	Monel Metal	"		0.0000138	256	"		"	0.0020						
Electrical Alloy Co.	Karma	Wrought		0.0000135	625	631	636	642	646	652	645	643	645	649	658
	Elalco Rayo	"		0 0000135	575	583	602	613	620	625	629	630	629	630	635
	Elalco Calido	"		0 000013	660	680	693	703	710	713	718	722	726	731	736
	Elalco Comet	"		0.000016	575	615	644	658	669	679	690	701	718	736	747
	Elalco Pure Nickel	"	0.142	0.000013	60	79	111	150	187	216	240	270	300	315	330
	Elalco Manganese Nickel	"	......	0.000013	80	94.5	118	148							
	Elalco Magno	"	......	0.000013	112	134	157	186							
	Elalco Ideal	"	0.065aq	......	296	296	296	296	296						
Hoskins Manufacturing Co.	Chromel A	Wrought		0.000016^{ar}	625	Mean te	mperatur	e coeffici	ent (20 -	1000°C.)	0.00011				
	Chromel B	"		0.000016^{ar}	540										
	Chromel C	"		0.000016^{ar}	655	Mean te	mperatur	e coefficie	nt (20 -	550° C.)	0.00018				
	Chromel D	"			523	"	"	"	(20 -	150° C.)	0.00060				
	Chromel Alloy No. 502	Cast		0.000016^{ar}											
	Copel	Wrought			298	Mean te	mperatur	e coeffici	ent (20 -	480° C.)	negligible				
	Alloy No. 484	"			......										
International Nickel Co.	Monel Metal	Wrought and Cast	0.06	a l	268^{aw} 256^{av}	310	326	338	352	359	371	384	399	411	437
	Nickel (Commercially Pure)	Wrought and Cast	0.140^{as}	b c	64^{au} 65^{av}	92	132	181	225	248	266	284	303	323	344
American Brass Co.	Tobin Bronze	Wrought		0 0000211^{bs}											
	Phosphor Bronze	"		0.0000190^{bs}	74.5										
	Nickel Silver	"			186.5	Temper	ature coe	fficient at	20° C. =	0.00033					
	Low Brass	"		0 0000191	31 6										
	Common High Brass	"		0.0000202	39 03										
	Ambrac Metal	"			175										
American Metal Products Co.	Ampco Bronze	Wrought and Cast													
Aterite Co., Inc.	Aterite	Wrought	0.077	0.0000165	158	Temper	ature coe	fficient at	0° C. 0.	000362					
		Cast	0.045^{bt}	0.0000148	298 - 326	"		"	" 0.	000365 -	0.000540				
Chapman Valve Manufacturing Co.	Davis Metal	Cast	0.045	0.0000144											
Chase Metal Works	Naval Brass	Wrought		0.0000214	41.6										
	Admiralty Tubing	"		0 0000202											
	Commercial Bronze Rod	"		0.0000185	28										
	18-per-cent Nickel Silver	"			185										
Curtis Bay Copper and Iron Works	Everbrite No. 90	Wrought^{bu}													
	Everbrite No. 92	" ^{bu}													
Dupont Engineering Co.	Everdur No. 50 Metal	Wrought and Cast		0.000017^{bh}	187										
Frontier Bronze Corp.	Titanium-Aluminum Bronze No. 1	Cast		0.0000171											
	Titanium-Aluminum Bronze No. 5	"		0.0000171											
Scovill Manufacturing Co.	Naval Brass	Wrought													
	Admiralty Metal	"													
	Admiralty Nickel	"													
	Spring Oreide	"													
Standard Calorimeter Co.	Illium	Cast		0.0000135^{bl}											

TABLE III.—THERMAL, ELECTRICAL AND CORROSION DATA ON CORROSION-RESISTA

Maximum Temperature for Continuous Operation in Air, deg. Cent.	Resistance to Various Corroding Media																
	Sulfuric Acid			Nitric Acid			Hydrochloric Acid			Acetic Acid			Sodium Hydroxide			Ammonium Hydr	
	Very Dilute	Moderate Dilution	Concentrated	Very Dilute	Moderate Dilution	Concentrated	Very Dilute	Moderate Dilution	Concentrated	Very Dilute	Moderate Dilution	Concentrated	Very Dilute	Moderate Dilution	Concentrated	Very Dilute	Moderate Dilution
800	Poor	Poor	Good	Good^{c}	Excellent	Excellent	Poor	Poor	Poor			Excellent		Excellent			
	1 per cent			1 per cent			1 per cent						10 per cent				
	Good			Excellent			Good						Excellent				
	Fair			"			"						"				
......	Poor	Poor	Poor	Excellent	Excellent	Excellent	Poor	Poor	Poor	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
1000	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"
	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
	Poor^{bp}	Poor	Poor	Poor	Fair	Excellent	Good	Good	Poor	Good	Good	Good	Excellent	Excellent	Excellent	Excellent	Excellent
......	10.0^{j}	13.4^{k}	......		21.4^{l}							4.7^{m}					
980			•		0.6^{p}	0.3^{q}			140.6^{r}			0.3^{s}					
1150												0.95^{v}					
	6.3^{j}	8.4^{k}	12.4^{w}														
	Good	Good		Excellent	Excellent		Fair	Fair		Excellent	Excellent		Excellent	Excellent		Excellent	Excellent
	Poor	Poor	Poor	Excellent	Excellent	Excellent	Poor	Poor	Poor	Good	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
													"	"	"	"	"
1000	Fair	Fair	Good	Excellent	Excellent	Excellent	Poor	Poor	Poor	Excellent	Excellent	Good	Excellent	Excellent	Excellent	Excellent	Excellent
930	Poor	Poor	"	"	"	"		Good (16 per cent acid)	"	"	"	"	"	"	"	"	"
950	"	"	"	"	"	"	Poor	Poor	"	"	"	"	Good	Good	Good	Good	Good
930																	
	Fair	Fair	Poor'	Excellent	Excellent	Excellent	Good	Good	Poor								
	"	"	"	"	"	"	"	"	"								
	"	"	"	"	"	"	"	"	"								
1150																	
......																	
1290																	
1200																	
900				Poor	Poor	Poor	Fair	Fair	Poor	Poor	Poor	Poor				Excellent	Excellent
1000		^{af}		"	"	"	"	"	"	"	"	"				"	"
1100		^{ag}															
1150		^{ag}															
600																	
1150																	
1150	Poor	Poor	Good	Excellent	Excellent	Excellent	Poor	Poor	Poor								
500	......																
......	......																
1100	Fair	Poor	Poor	Excellent	Excellent	Excellent	Poor	Poor	Poor	Good	Good	Good	Good	Good	Good	Good	Good
1000		Good	Good		Excellent	Excellent		Poor	Poor		Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
	0.5 per cent	20 per cent		0.5 per cent	20 per cent		0.5 per cent	20 per cent		0.5 per cent	20 per cent						
	0.0000057^{ao}	0.0000039	0.0000016	None	0.0000017	0.0000015	0.00012	0.00667	0.01822	None	None	0.0000015					
	0.5 per cent	20 per cent		0.5 per cent	20 per cent		0.5 per cent	20 per cent		0.5 per cent	20 per cent						
	0.00013	0.000071	0.0000063	0.0000028	0.000033	0.00016	0.0014	0.028	0.1017	None	None	0.0000023					
	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Fair	Good	Fair	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
1100																	
1100																	
1000																	
1000																	
1100	Excellent	Excellent	Good	Good	Good	Good	Good	Good	Fair	Excellent	Excellent	Good	Excellent	Excellent	Good	Excellent	Excellent
1100	"	"	"	"	"	"	"	"	"	"	"	"	"	"		"	"
1000	"	"	"	"	"	"	"	"	"	"	"		"	"	Excellent	"	"
700	Good	Good	Fair	Fair	Fair	Poor	Fair	Fair	Fair	Good	Good		"	"	"	"	"
650	"	"	"	"	"	"	Good	Good	"	"	"	Good	"	"	"	"	"
650	"	"	Good	"	"	"	"	"	"	"	"		"	"	"	"	"
650	"	"	"	"	"	"	"	"	"	"	"	"					
500	......																
1150		0.04^{as}	0.09		1.0	0.08		0.05	5.0					0.0001			
1100		to	to		to	to		to	to		0.03	0.30		to			
1000		0.05	0.10		7.0	0.30		0.30	6.0					0.001			
600																	
425																	
......																	
800	1 per cent	20 per cent	0.00044 –	0.7 per cent	25 per cent	Poor	0.3 per cent	20 per cent	0.0082 –	1 per cent	25 per cent	99 per cent			Excellent	Good^{bo}	
	0.00009 –	0.00025	0.0018	0.00232	0.077 – 0.089		0.00037	0.0008	0.0094	0.00016	0.00024	0.00018 –					
	0.00031$^{as\ aw}$											0.00022					
1300	^{as}	10 per cent	Good		32 per cent	Poor	Good	Good	0.00489			Good	Excellent	Excellent	Excellent	Good	
	^{aw}	0.00026			0.204												
	Good	Good		Poor	Poor	Poor	Good	Good					Good	Good		Poor	Poor
	"	"		"	"	"	Poor	Poor	Poor	Fair	Fair	Fair	"	"		"	"
100																	
	Good	Good		Poor	Poor	Poor	Fair	Fair					Good	Good		Poor	Poor
	Fair	Fair		"	"	"	"	"		Fair	Fair		"	"		"	"
	Excellent	Excellent	Good	"	"	"	Poor	Poor	Poor	Good	Good		Excellent	Excellent		"	"
			(cold)														
	Excellent	Excellent	Excellent	Poor	Poor	Poor	Good	Good	Good	Good	Good	Good				Fair	Fair
	Excellent	Excellent	Excellent	Poor	Poor	Poor	Not reco	mmended					Excellent	Excellent	Excellent	Not reco	mmended
	"	"	"	"	"	"	"	"					"	"	"	"	"
	10 per cent	30 per cent	Excellent				10 per cent							10 per cent			10 per cent
	0.00035^{bf}	0.00027					0.0091							0.00046			0.00081
	Good	Fair		Poor	Poor	......	Fair	Fair					Good	Good		Depends o	n temperature
	"			Fair	"	Poor	"	Poor	Poor				"	"		"	"
	Excellent	Good				......	Good						"	"		Good	Good
	Good		Poor		Poor	Poor	"	Fair	Fair	Good	Good	Good	"	"	Good	"	"
	1 per cent	10 per cent	50 per cent				2 per cent				10 per cent			10 per cent			
	9.4	17.1	11.6				186.5				19.8			0			
	27.9	12.9	10.0				182.6				20.6			0			
	^{bi}	20 per cent	70 per cent	Poor	Poor	Poor		20 per cent	0.000224	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Fair	Fair
		0.00011	0.00004					0.00023									
	Good	Good	Good				Good	Good	Good								
	"	"	"				"	"	"								
	......	......															
	......	......															
	2 per cent	5 per cent															
	0.18^{bk}	0.40															
	2 per cent	5 per cent															
	0.52^{bn}	0.32															
	10 per cent	25 per cent	95 per cent	10 per cent	25 per cent	70 per cent	5 per cent	25 per cent				99 per cent	Excellent	Excellent	Excellent	Excellent	Excellent
	1.87^{bm}	1.03	0.19	0.19	0.52	1.55	32.9	224				0					
	10 per cent	25 per cent	95 per cent	10 per cent	25 per cent	70 per cent	5 per cent	10 per cent				99 per cent					
	23.9	49.7	32.9	11.6	22.6	29.7	851	1071				3.87					

TABLE III.—THERMAL, ELECTRICAL AND CORROSION DATA ON CORROSION-RESISTANT, HEAT-RESISTAN

Resistance to Various Corroding Media

lfuric Acid		Nitric Acid			Hydrochloric Acid			Acetic Acid			Sodium Hydroxide			Ammonium Hydroxide			Sea Water
Moderate Dilution	Concentrated	Very Dilute	Moderate Dilution	Concentrated	Very Dilute	Moderate Dilution	Concentrated	Very Dilute	Moderate Dilution	Concentrated	Very Dilute	Moderate Dilution	Concentrated	Very Dilute	Moderate Dilution	Concentrated	
Poor	Good	Good[c]	Excellent	Excellent	Poor	Poor	Poor			Excellent		Excellent					3.1[d]
		1 per cent Excellent "			1 per cent Good "						10 per cent Excellent "						Good Excellent
Poor "	Poor "	Excellent "	Excellent "	Excellent "	Poor "	Poor "	Poor "	Excellent "	Excellent "	Excellent "	Excellent "	Excellent "	Excellent "	Excellent "	Excellent "	Excellent "	Good Excellent
......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	
Poor	Poor	Poor	Fair	Excellent	Good	Good	Poor	Good	Good	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	
13.4[k]	......	-	21.4[l]							4.7[m]							......
	•		0.6[p]	0.3[q]		–	140.6[r]			0.3[s]							0.03[t]
										0.95[v]							
8.4[k]	12.4[w]																
Good		Excellent	Excellent		Fair	Fair		Excellent	Excellent		Excellent	Excellent		Excellent	Excellent		Excellent
Poor	Poor	Excellent	Excellent	Excellent	Poor	Poor	Poor	Good	Good	Excellent	Excellent "	Excellent "	Excellent "	Excellent "	Excellent "	Excellent "	Good
Fair	Good	Excellent	Excellent	Excellent	Poor	Poor Good (16 per cent acid)	Poor	Excellent	Excellent	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Poor "	" "	" "	" "	" "	Poor	Poor	" "	" "	" "	" "	" Good	" Good	" Good	" Good	" Good	" Good	" Poor
Fair "	Poor' " "	Excellent " "	Excellent " "	Excellent " "	Good " "	Good " "	Poor " "										Excellent " "
		Poor	Poor	Poor	Fair	Fair	Poor	Poor	Poor	Poor				Excellent	Excellent	Excellent	
a f		"	"	"	"	"	"	"	"	"				"	"	"	
ag																	
ag																	
Poor	Good	Excellent	Excellent	Excellent	Poor	Poor	Poor										Excellent ....
Poor	Poor	Excellent	Excellent	Excellent	Poor	Poor	Poor	Good	Good	Good	Good	Good	Good	Good	Good	Good	Excellent
Good	Good		Excellent	Excellent		Poor	Poor		Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
20 per cent 0.0000039 20 per cent 0.000071	0.0000016 0.0000063	0.5 per cent None 0.5 per cent 0.0000028	20 per cent 0.0000017 20 per cent 0.000033	0.0000015 0.00016	0.5 per cent 0.00012 0.5 per cent 0.0014	20 per cent 0.00667 20 per cent 0.028	0.01822 0.1017	0.5 per cent None 0.5 per cent None	20 per cent None 20 per cent None	0.0000015 0.0000023							None
Excellent	Excellent	Excellent	Excellent	Excellent	Fair	Good	Fair	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent[ap]
Excellent	Good	Good	Good	Good	Good	Good	Fair	Excellent	Excellent	Good	Excellent	Excellent	Good	Excellent	Excellent	Good	Excellent
"	"	"	"	"	"	"	"	"	"	"	" "	" "	Excellent	" "	" "	Excellent	"
Good "	Fair "	Fair "	Fair "	Poor "	Fair Good	Fair Good	Fair "	Good "	Good "	Good	" "	" "	" "	" "	" "	" "	Fair Excellent
"	Good	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"
"	"	"	"	"		"	"	"	"	"	"	"	"	"	"	"	
0.04[as] to 0.05	0.09 to 0.10		1.0 to 7.0	0.08 to 0.30		0.05 to 0.30	5.0 to 6.0		0.03	0.30		0.0001 to 0.001					
0 per cent 0.00025	0.00044 – 0.0018	0.7 per cent 0.00232	25 per cent 0.077 – 0.089	Poor	0.3 per cent 0.00037	20 per cent 0.0008	0.0082 – 0.0094	1 per cent 0.00016	25 per cent 0.00024	99 per cent 0.00018 – 0.00022			Excellent	Good[bo]		Anhydrous Liquid 0.00016	0.000007 – 0.000011
0 per cent 0.00026	Good		32 per cent 0.204	Poor	Good	Good	0.00489			Good	Excellent	Excellent	Excellent	Good		Anhydrous Liquid 0.00014	Excellent
Good "		Poor "	Poor "	Poor "	Good Poor	Good Poor	Poor	Fair	Fair	Fair	Good "	Good "		Poor "	Poor "	Poor "	Excellent
Good Fair		Poor "	Poor "	Poor "	Fair "	Fair "					Good "	Good "		Poor "	Poor "	Poor "	Excellent Fair
Excellent	Good (cold)	"	"	"	Poor	Poor	Poor	Fair Good	Fair Good		Excellent	Excellent		"	"	"	Excellent
Excellent	Excellent	Poor	Poor	Poor	Good	Good	Good	Good	Good	Good				Fair	Fair	Fair	Excellent
Excellent	Excellent	Poor	Poor	Poor	Not reco	mmended					Excellent	Excellent	Excellent	Not reco	mmended		
"	"	"	"	"	"	"					"	"	"	"	"		
0 per cent 0.00027	Excellent				10 per cent 0.0091							10 per cent 0.00046			10 per cent 0.00081		Excellent
Fair		Poor Fair	Poor "	...... Poor	Fair "	Fair Poor	Poor				Good "	Good "		Depends o "	n temperature "		Excellent "
Good	Poor		Poor	...... Poor	Good "	Fair	Fair	Good	Good	Good	" "	" "	Good	Good "	Good "	Good	Good "
0 per cent 17.1 12.9	50 per cent 11.6 10.0				2 per cent 186.5 182.6				10 per cent 19.8 20.6			10 per cent 0 0					
0 per cent 0.00011	70 per cent 0.00004	Poor	Poor	Poor		20 per cent 0.00023	0.000224	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Fair	Fair	Fair	0.000028 (Spray)
Good	Good				Good	Good	Good										Good
"	"				"	"	"										"
....																	
5 per cent 0.40 5 per cent 0.32																	
5 per cent 1.03 5 per cent 49.7	95 per cent 0.19 95 per cent 32.9	10 per cent 0.19 10 per cent 11.6	25 per cent 0.52 25 per cent 22.6	70 per cent 1.55 70 per cent 29.7	5 per cent 32.9 5 per cent 851	25 per cent 224 10 per cent 1071				99 per cent 0 99 per cent 3.87	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent

SISTANT AND ELECTRICAL-RESISTANCE ALLOYS.

Sea Water	Sea Air	Moist Atmosphere	Moist Sulfurous Atmosphere	Mine Waters	Chlorine in Aqueous Solution	Gases Containing Carbon Monoxide	Miscellaneous Corrosion Data	Designation of Material	Manufacturer
.1[d]			987[e]		Good		Resistant to molten Sn, Pb, type metal; also immune to attack of many organic acids, solutions of many carbonates, nitrates and sulfates. CH$_3$Cl. ZnCl$_2$; not good for molten Zn or NaNO$_2$ or for acetic acid at 90° C.; no loss at 800° C. (50-hr. test, atmosphere not stated).	Ascoloy	Allegheny Steel Co.
ood ellent		Good Excellent				Fair Good	10 per cent KOH—excellent (An. and H. T.); 10 per cent citric acid—good (An. and H. T.); K$_2$CO$_3$—excellent (An. and H. T.); Alumn—fair (An.), good (H. T.).[br]	Atlas Stainless	Atlas Steel Corp.
ood	Excellent	Excellent	Poor		Poor	Excellent	Resistance to saturated or superheated steam, excellent.	Carpenter Stainless	Carpenter Steel Co.
ellent	"	"	Excellent		"	"	Good in molten brass and other non-ferrous metals.	Carpenter Rustless	
							Not recommended for use with acids. Does not pit and is easily cleaned. Much better in corroding media than carbon steel.	30-per-cent Nickel Steel	
								Corrosion-Resistant Steel	
...		......					21 hr., room temperature, chrome alum fixing bath, 4.7 mg. per sq. in.; 4 hr. 0.001 HgCl$_2$, room temperature, 2.7 mg. per sq. in.; 85 per cent H$_3$PO$_4$, 90° C., 6 hr., 140 mg. per sq. in.[n]	No. 2600 Metal	Crucible Steel Co.
3[t]		Excellent		0.00015 – 0.0422[u]				Rezistal No. 4	
							21 hr. room temperature, chrome alum fixing bath, no loss; 15 per cent lactic acid 24 hr. or 30 per cent lactic acid 7 hr., 90–100° C., no loss; 0.001 HgCl$_2$ 4 hr. room temperature, no loss; 85 per cent H$_3$PO$_4$, 2 hr., 90–100° C., 1.3 mg. per sq. in.	Rezistal No. 7	
								Rezistal No. 8	
llent	Excellent	Excellent	Excellent	Good	Fair	Good		No. 17 Metal	Cyclops Steel Co.
od	Excellent	Excellent	Poor		Poor		Sulfates and chlorides generally attack this steel.	S-less Stainless Steel	Firth-Sterling Steel Co.
					......			S-less Stainless Iron	
llent	Excellent	Excellent	Excellent	Excellent		Excellent	O.K. in lead at 1000° C. Excellent for nitric or acetic acid at boiling point. No weight loss due to scaling, up to 1000° C.	Delhi Tough Iron	Ludlum Steel Co.
.	"	"	"	"		"	Good in nitric or acetic acid at boiling point. No weight loss due to scaling up to 930° C.	Delhi Hard	
or	Poor	Poor	Poor	"	Poor	"	O.K. in lead at 950° C. Excellent for nitric or acetic acid at boiling point. No weight loss due to scaling up to 950° C.	Silcrome	
							Not immune to corrosive influences, but initial oxide coating protects metal against progressive corrosion; poor in acids. No weight loss due to scaling up to 930° C.	Silcrome, Grade F	
llent	Excellent	Excellent					Excellent for steam service.	Stainless Steel (Low C)	The Midvale Co.
.	"	"					" " " "	Stainless Steel (Med. C)	
.	"	"					" " " .	Stainless Steel (High C)	
								Stainless Steel	Vanadium Alloys Steel Co.
						Good	Good in molten lead and molten salt baths (except cyanide). No reaction with carbonizing compounds or cool distillates.	Calite A	The Calorizing Co.
						......		Calite B	
								Fire Armor	Chrobaltic Tool Co.
								Q-Alloys	General Alloys Co.
							Loss in weight, 500 hr. at 1750° F. (atmosphere not stated), 14 per cent.	Misco Metal	Michigan Steel Casting Co.
		Excellent		Excellent				Nichrome	Driver-Harris Co.
		"		"			Deteriorated by hot sulfur-bearing gases. O.K. in lactic acid. O.K. in molten tin and silver. Not good in sodium compounds at elevated temperature, particularly carbonizing compounds containing Na$_2$CO$_3$; BaCO$_3$ less destructive.	Nichrome	
							Oxide is thin, quite impervious and adherent and so prevents further oxidation; does not flake on repeated heating and cooling.	Nichrome III	
							Alternate heating and cooling does not cause growth of metal.	Nichrome IV	
								No 193 Alloy	
								Cimet.	
llent	Excellent	Excellent		Excellent			Resistant to fruit acids and to sulfur-bearing gases at elevated temperatures.	Cimet	
..								Advance	
..								Manganin	
lent	Excellent	Excellent	Good	Excellent	Poor	Excellent	Excellent in phosphoric, citric and other fruit acids. Excellent resistance to molten Ag; good resistance to molten brass, salt and niter baths.	Chrome Iron, Duraloy, Cimet	Cutler Steel Co. and Driver-Harris Co., licensees of Electro-Metallurgical Co.
lent	Excellent	Excellent	Fair	Excellent	Fair		Excellent in iodine, 10 per cent trichloracetic acid. Good in 1/500 HgCl$_2$, conc. HF, fair in 6 per cent H$_2$SO$_2$.[al]	Stellite	Haynes Stellite Co.
ne	None	None	Slight tarnish	0.0000063			Excellent for arsenic salts, sulfates, chlorides, nitrates, phosphates and organic acids. Not good for fused alkalis, Br, HF or chlorides of S.	Duriron	The Duriron Co.
lent[ap]	Excellent[ap]	Excellent[ap]	Excellent	Good	Fair		Resists most corrosives extremely well.	Corrosiron	Pacific Foundry Co. Bethlehem Foundry and Machine Co.
								Superior Nickel Chrome	Alloy Metal Wire Co.
								Peerless Nickel Chrome	
								Premier Nickel Chrome	
								Silchrome	
								Acme Nickel Steel	
								Pure Nickel	
								Manganese Nickel	
								Excelsior	
								Monel Metal	
lent	Excellent	Excellent			Fair			Karma	Electrical Alloy Co.
	"	"			"			Elalco Rayo	
	"	"			"			Elalco Calido	
r	Fair	Fair			"			Elalco Comet	
ent	Excellent	Excellent			"			Elalco Pure Nickel	
	"	"			"			Elalco Manganese Nickel	
	"	"			"			Elalco Magno	
					......			Elalco Ideal	
							Excellent for molten lead and white metals and fairly resistant to cyanide and other molten salts. Suitable as stirrers for molten brass and aluminum, but not as containers for these metals.	Chromel A	Hoskins Manufacturing Co.
								Chromel B	
								Chromel C	
								Chromel D	
								Chromel Alloy No. 502	
								Copel	
								Alloy No. 484	
07 – 011	Excellent	Excellent	Fair	Excellent[ay]	Good	Excellent	Under 800° C., resists action of caustic alkalis, carbonates, cyanides, chlorides, etc., but not resistant to action of Al, Sn, Zn, Pb, etc.[az]	Monel Metal	International Nickel Co.
ent	Excellent	Excellent	Fair	Excellent	Fair	Excellent	Resists action of caustic alkalis, carbonates, cyanides, chlorides, etc. Not recommended, for use with molten metals.[bd]	Nickel (Commercially Pure)	
ent	Excellent	Excellent						Tobin Bronze	American Brass Co.
		Good					Good in sulfite solutions.	Phosphor Bronze	
								Nickel Silver	
ent	Excellent	Excellent	Excellent	Fair				Low Brass	
	Fair	Good						Common High Brass	
ent	Excellent	Excellent	Good	Fair	Excellent[bt]		Excellent in laundrying solutions.	Ambrac Metal	
ent	Excellent	Excellent	Excellent	Excellent				Ampco Bronze	American Metal Products Co.
			Excellent	....			Recommended for many chlorides, sulfates and salts of organic acids, also many of these acids, not for oxidizing acids or mixtures or H$_3$PO$_4$.		
			"	Excellent			Similar to wrought Aterite; also good in superheated steam up to 675° C.	Aterite	Aterite Co., Inc.
ent	Excellent	Excellent			0.0044		No attack by formic, oxalic, citric, tannic, boric or common fatty acids at 150° F., nor by fuel oil, dry Cl or many organic volatile solvents at normal temperature.[bg]	Davis Metal	Chapman Valve Manufacturing Co.
ent	Excellent	Excellent	Good	......				Naval Brass	Chase Metal Works
	"	"	Fair	Poor				Admiralty Tubing	
d	Good	"	Excellent					Commercial Bronze Rod	
	"	"	Fair		Poor			18-per-cent Nickel Silver	
								Everbrite No. 90	Curtis Bay Copper and Iron Works
								Everbrite No. 92	
028 y)	Excellent	Excellent	Excellent	0.00052 (Velocity 8 ft. per sec.)	0.0016 (12.5 g. Cl per liter)		No permanent expansion or growth on heating between room temperature and 1000° F.[bj]	Everdur No. 50 Metal	Dupont Engineering Co.
d	Good	Good						Titanium-Aluminum Bronze No. 1	Frontier Bronze Corp.
	"	"						Titanium-Aluminum Bronze No. 5	
								Naval Brass	Scovill Manufacturing Co.
								Admiralty Metal	
								Admiralty Nickel	
								Spring Oreide	
ent	Excellent	Excellent	Excellent	Excellent	Poor	Excellent		Illium	Standard Calorimeter Co.

NT, HEAT-RESISTANT AND ELECTRICAL-RESISTANCE ALLOYS.

oxide	Sea Water	Sea Air	Moist Atmosphere	Moist Sulfurous Atmosphere	Mine Waters	Chlorine in Aqueous Solution	Gases Containing Carbon Monoxide	Miscellaneous Corrosion Data	Designation of Material
Concentrated									
	3.1[d]			987[e]		Good		Resistant to molten Sn, Pb, type metal; also immune to attack of many organic acids, solutions of many carbonates, nitrates and sulfates, CH_3Cl, $ZnCl_2$; not good for molten Zn or $NaNO_2$ or for acetic acid at 90° C.; no loss at 800° C. (50-hr. test, atmosphere not stated).	Ascoloy
	Good Excellent		Good Excellent				Fair Good	10 per cent KOH—excellent (An. and H. T.); 10 per cent citric acid—good (An. and H. T.); K_2CO_3—excellent (An. and H. T.); Alumn—fair (An.), good (H. T.).[br]	Atlas Stainless
Excellent	Good	Excellent	Excellent	Poor		Poor	Excellent	Resistance to saturated or superheated steam, excellent.	Carpenter Stainless
"	Excellent	"	"	Excellent		"	"	Good in molten brass and other non-ferrous metals.	Carpenter Rustless
......								Not recommended for use with acids. Does not pit and is easily cleaned. Much better in corroding media than carbon steel.	30-per-cent Nickel Steel
Excellent									Corrosion-Resistant Steel
	......		......					21 hr., room temperature, chrome alum fixing bath, 4.7 mg. per sq. in.; 4 hr. 0.001 $HgCl_2$, room temperature, 2.7 mg. per sq. in.; 85 per cent H_3PO_4, 90° C., 6 hr., 140 mg. per sq. in.[n]	No. 2600 Metal
	0.03[t]		Excellent		0.00015 – 0.0422[u]				Rezistal No. 4
								21 hr. room temperature, chrome alum fixing bath, no loss; 15 per cent lactic acid 24 hr. or 30 per cent lactic acid 7 hr., 90–100° C., no loss; 0.001 $HgCl_2$ 4 hr. room temperature, no loss; 85 per cent H_3PO_4, 2 hr., 90–100° C., 1.3 mg. per sq. in.	Rezistal No. 7
									Rezistal No. 8
	Excellent	Excellent	Excellent	Excellent	Good	Fair	Good		No. 17 Metal
Excellent	Good	Excellent	Excellent	Poor		Poor		Sulfates and chlorides generally attack this steel.	S-less Stainless Steel
"						......			S-less Stainless Iron
Excellent	Excellent	Excellent	Excellent	Excellent	Excellent		Excellent	O.K. in lead at 1000° C. Excellent for nitric or acetic acid at boiling point. No weight loss due to scaling, up to 1000° C.	Delhi Tough Iron
"	"	"	"	"	"		"	Good in nitric or acetic acid at boiling point. No weight loss due to scaling up to 930° C.	Delhi Hard
Good	Poor	Poor	Poor	Poor	"	Poor	"	O.K. in lead at 950° C. Excellent for nitric or acetic acid at boiling point. No weight loss due to scaling up to 950° C.	Silcrome
								Not immune to corrosive influences, but initial oxide coating protects metal against progressive corrosion; poor in acids. No weight loss due to scaling up to 930° C.	Silcrome, Grade F
	Excellent	Excellent	Excellent					Excellent for steam service.	Stainless Steel (Low C)
	"	"	"					" " " "	Stainless Steel (Med. C)
	"	"	"					" " " "	Stainless Steel (High C)
									Stainless Steel
							Good	Good in molten lead and molten salt baths (except cyanide). No reaction with carbonizing compounds or cool distillates.	Calite A
							......		Calite B
									Fire Armor
									Q-Alloys
								Loss in weight, 500 hr. at 1750° F. (atmosphere not stated), 14 per cent.	Misco Metal
Excellent			Excellent		Excellent				Nichrome
"			"		"			Deteriorated by hot sulfur-bearing gases. O.K. in lactic acid. O.K. in molten tin and silver. Not good in sodium compounds at elevated temperature, particularly carbonizing compounds containing Na_2CO_3; $BaCO_3$ less destructive.	Nichrome
								Oxide is thin, quite impervious and adherent and so prevents further oxidation; does not flake on repeated heating and cooling.	Nichrome III
								Alternate heating and cooling does not cause growth of metal.	Nichrome IV
									No. 193 Alloy
									Cimet.
	Excellent	Excellent	Excellent		Excellent			Resistant to fruit acids and to sulfur-bearing gases at elevated temperatures.	Cimet
	......								Advance
	......								Manganin
Good	Excellent	Excellent	Excellent	Good	Excellent	Poor	Excellent	Excellent in phosphoric, citric and other fruit acids. Excellent resistance to molten Ag; good resistance to molten brass, salt and niter baths.	Chrome Iron, Duraloy, Cimet
Excellent	Excellent	Excellent	Excellent	Fair	Excellent	Fair		Excellent in iodine, 10 per cent trichloracetic acid. Good in 1/500 $HgCl_2$, conc. HF, fair in 6 per cent H_2SO_4.[al]	Stellite
	None	None	None	Slight tarnish	0.0000063			Excellent for arsenic salts, sulfates, chlorides, nitrates, phosphates and organic acids. Not good for fused alkalis, Br, HF or chlorides of S.	Duriron
Excellent	Excellent[ap]	Excellent[ap]	Excellent[ap]	Excellent	Good	Fair		Resists most corrosives extremely well.	Corrosiron
									Superior Nickel Chrome
									Peerless Nickel Chrome
									Premier Nickel Chrome
									Silchrome
									Acme Nickel Steel
									Pure Nickel
									Manganese Nickel
									Excelsior
									Monel Metal
Good	Excellent	Excellent	Excellent			Fair			Karma
"	"	"	"			"			Elalco Rayo
Excellent	"	"	"			"			Elalco Calido
"	Fair	Fair	Fair			"			Elalco Comet
"	Excellent	Excellent	Excellent			"			Elalco Pure Nickel
"	"	"	"			"			Elalco Manganese Nickel
"	"	"	"			"			Elalco Magno
						......			Elalco Ideal
								Excellent for molten lead and white metals and fairly resistant to cyanide and other molten salts. Suitable as stirrers for molten brass and aluminum, but not as containers for these metals.	Chromel A
									Chromel B
									Chromel C
									Chromel D
									Chromel Alloy No. 502
									Copel
									Alloy No. 484
Anhydrous Liquid 0.00016	0.000007 – 0.000011	Excellent	Excellent	Fair	Excellent[ay]	Good	Excellent	Under 800° C., resists action of caustic alkalis, carbonates, cyanides, chlorides, etc., but not resistant to action of Al, Sn, Zn, Pb, etc.[az]	Monel Metal
Anhydrous Liquid 0.00014	Excellent	Excellent	Excellent	Fair	Excellent	Fair	Excellent	Resists action of caustic alkalis, carbonates, cyanides, chlorides, etc. Not recommended for use with molten metals.[bd]	Nickel (Commercially Pure)
Poor	Excellent	Excellent	Excellent						Tobin Bronze
"			Good					Good in sulfite solutions.	Phosphor Bronze
									Nickel Silver
Poor	Excellent	Excellent	Excellent	Excellent	Fair				Low Brass
"	Fair	Fair	Good						Common High Brass
"	Excellent	Excellent	Excellent	Good	Fair	Excellent[bf]		Excellent in laundrying solutions.	Ambrac Metal
Fair	Excellent	Excellent	Excellent	Excellent	Excellent				Ampco Bronze
				Excellent	....			Recommended for many chlorides, sulfates and salts of organic acids, also many of these acids, not for oxidizing acids or mixtures or H_3PO_4.	
				"	Excellent			Similar to wrought Aterite; also good in superheated steam up to 675° C.	Aterite
	Excellent	Excellent	Excellent			0.0044		No attack by formic, oxalic, citric, tannic, boric or common fatty acids at 150° F., nor by fuel oil, dry Cl or many organic volatile solvents at normal temperature.[bg]	Davis Metal
	Excellent	Excellent	Excellent	Good	......				Naval Brass
	"	"	"	Fair	Poor				Admiralty Tubing
	Good	Good	"	Excellent					Commercial Bronze Rod
Good	"	"	"	Fair		Poor			18-per-cent Nickel Silver
									Everbrite No. 90
									Everbrite No. 92
Fair	0.000028 (Spray)	Excellent	Excellent	Excellent	0.00052 (Velocity 8 ft. per sec.)	0.0016 (12.5 g. Cl per liter)		No permanent expansion or growth on heating between room temperature and 1000° F.[bj]	Everdur No. 50 Metal
	Good	Good	Good						Titanium-Aluminum Bronze No. 1
	"	"	"						Titanium-Aluminum Bronze No. 5
									Naval Brass
									Admiralty Metal
									Admiralty Nickel
									Spring Oreide
Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Poor	Excellent		Illium

PLATE III.
PROC. AM. SOC. TESTING MATS.
VOL. 24, PART II.
SYMPOSIUM ON CORROSION-RESISTANT, HEAT-RESISTANT AND ELECTRICAL-RESISTANCE ALLOYS.

aterial	Manufacturer
	Allegheny Steel Co.
	Atlas Steel Corp.
eel Steel	Carpenter Steel Co.
	Crucible Steel Co.
	Cyclops Steel Co.
	Firth-Sterling Steel Co.
	Ludlum Steel Co.
) C) C)	The Midvale Co.
	Vanadium Alloys Steel Co.
	The Calorizing Co.
	Chrobaltic Tool Co.
	General Alloys Co.
	Michigan Steel Casting Co.
	Driver-Harris Co.
Cimet	Cutler Steel Co. and Driver-Harris Co., licensees of Electro-Metallurgical Co.
	Haynes Stellite Co.
	The Duriron Co.
	Pacific Foundry Co. Bethlehem Foundry and Machine Co.
e e e	Alloy Metal Wire Co.
kel	Electrical Alloy Co.
	Hoskins Manufacturing Co.
Pure)	International Nickel Co.
	American Brass Co.
	American Metal Products Co.
	Aterite Co., Inc.
	Chapman Valve Manufacturing Co.
d er	Chase Metal Works
	Curtis Bay Copper and Iron Works
	Dupont Engineering Co.
ronze ronze	Frontier Bronze Corp.
	Scovill Manufacturing Co.
	Standard Calorimeter Co.

NOTES

[a] Approximately $\frac{7}{16}$ that of copper.

[b] At 1100° C.

[c] Attacked by extremely dilute solutions only.

[d] Loss in mg. per sq. in.; 5 per cent NaCl, aerated, 200 hr.

[e] " " " " " SO_2 + steam, 23 days.

[f]	23 - 250° C	0.0000099
	250 - 500° C	0.0000105
	500 - 700° C	0.0000104
[g]	20 - 300° C	0.0000161
	300 - 600° C	0.0000180
	600 - 900° C	0.0000202

[h] Value at 0° C.

[i] Average temperature coefficient of electrical resistance, 0.00029 (0 - 1000° F.).
" " " " " " 0.000135 (1000 - 1800° F.)

[j] Loss in mg. per sq. in., 5 per cent H_2SO_4, 90° C., 14 hr.

[k] " " " 10 per cent H_2SO_4, 90° C., 7 hr.

[l] " " " 1.20 sp. gr., HNO_3, room temperature, 96 hr.

[m] " " " glacial acetic, 90 - 100° C. 2 hr.

[n] " " " saturated boiling NH_4Cl, 3½ hr. = 3.8.
15 per cent lactic acid, 48 hr., 90 - 100° C. = 21.8.
2 hr. at 2000° F. (atmosphere not stated) = 100.
7 hr. at 1300° F. (atmosphere not stated) = 2.75.

[o] Loss in mg. per sq. in., 4 days, 80° C.

10 per cent Oleum	1.6	100 per cent H_2SO_4	0.9
20 per cent "	1.2	66° Be. "	0.3
30 per cent "	1.2	60° " "	19.9
		50° " "	85.7

[p] Loss in mg. per sq. in., 4 days, 80° C., 1.07 sp. gr. HNO_3.

[q] " " " 4 days, " 96 per cent "

[r] " " " 5 hr., " 20° Be HCl.

[s] " " " 4 days, " glacial acetic.

[t] " " " 8 days, room temperature.

[u] Loss in mg. per sq. cm. per day.

[v] " mg. per sq. in., 6 hr., 90 - 100° C.

[w] " mg. per sq. in., 7 ar., 90° C., 20 per cent H_2SO_4.

[x] All data on this line same as [ao] except at 90° C.

[y] Average coefficient of electrical resistance, 20 - 1000° C., 0.0008.

[z] " for 20 - 200° C.

[ab] Data on corrosion are for steel properly hardened and tempered.

[ac] 0.5 per cent at room temperature to 1500° F. (total expansion).

[ad] Mean value, 0 - 800° C.

[ae] Approximate.

[af] 333 hr. tests at 20° C. (10 g. sample, 125 cc. acid).

Specific Gravity	Loss, g. per sq. in. per hr.
1.830	0.00007
1.747	0.00019
1.408	0.000
1.142	0.000
1.036	0.00006

Same conditions except 24.5 hr. at 80° C. followed by 47 hr. at 20° C.

Specific Gravity	Loss
1.830	0.0014
1.408	0.0010
1.036	0.0004

Loss in sulfurous acid, 6 times that for 1.830 sp. gr. H_2SO_4.

[ag] Resistance to various corrosives similar to Nichrome, but somewhat superior.

[ah] 1 per cent, 0 - 800° C. (total expansion).

[ai] May be varied within wide limits by slight composition changes.

[aj] Approximately one-half that of low-carbon steel.

[ak] According to composition.

[al] Resistance to all corrosives listed increases with increase of W content.

[am] Mean value, 20 - 600° C.

[an] Value at 18° C.

[ao] All values for this material on this line are losses in inches thickness per month, solutions agitated and exposed to diffused daylight (room temperature).

[ap] Surface rusts.

[aq] At 100° C.

[ar] Mean value, 20 - 1000° C.

[as] Values for this material are penetration in inches per month. Values in table are for room temperature.

[at]	25 - 100° C	0.000014
	25 - 300° C	0.000015
	25 - 600° C	0.000016

[au] Accidental value of sample on which high temperature tests were made.

[av] Mean value.

[aw] All values in the table for this material obtained with solutions neither agitated nor aerated.

[ax]

Boiling 1 per cent H_2SO_4 (not aerated)	0.0034 (see [as]).
" 0.7 " HNO_3 " "	0.020
" 0.3 " HCl " "	0.00314
1 per cent HCl, room temperature (unagitated, not aerated)	0.00046
20 per cent " 80° C. " " "	0.25
Boiling 1 per cent acetic (not aerated)	0.0021
" 99 " " " "	0.04 - 0.11
" 2.5 " NaOH " "	0.000044
" 20 " " " "	0.000004
0.53 per cent H_2SO_4 (agitated and aerated) room temperature	0.00152
25 " " " " " " "	0.00114
93 " " " " " " "	0.0065
28 " NH_4OH " ,not " " "	0.00239

Thickness of scale after two weeks in current of air at following temperatures:

600° C	< 0.001 in.
700° C	0.005 "
800° C	0.008 "
900° C	0.220 "
1000° C	0.250 "

[ay] In presence of ferric salts, rated as "Fair."

[az]

Value at −200° C	0.125
0° C	0.140
200° C	0.135
400° C	0.116
600° C	0.088
800° C	0.068
1000° C	0.065
1200° C	0.057

[bc]	25 - 100° C	0.000013
	25 - 300° C	0.0000145
	25 - 600° C	0.0000155

[bd]

5 per cent H_2SO_4 (unagitated, not aerated) 38 - 49° C	0.00141 (see [as])
5 " HNO_3 " " " " "	0.00635
5 " acetic " " " 100° C	0.00197 - 0.00214
28 " NH_4OH (agitated, not aerated) room temperature	0.00277

Thickness of scale after two weeks in current of air at following temperatures:

600° C	< 0.001 in.
700° C	< 0.001 "
800° C	< 0.001 "
900° C	0.004 "
1000° C	0.008 "

[be] At 140° C., 0.055.

[bf] Tests recorded on this line are in. penetration per month in solutions at 140 or 150° F. with agitation at the rate of 2.5 in. per min., except for Cl in aqueous solution (70° F., 0 velocity). All tests cover 60 to 90 day period.

[bg] Other tests as follows:

Medium	Temperature, deg. Fahr.	Velocity, in. per min.	Loss, in. penetration per month
48 per cent HF	70	0	0.00017
60 per cent Chromic Acid	160	2.5	0.00027
85 per cent H_3PO_4	70	0	0
Picric Acid	70	...	0
" "	170	2.5	0.0048
$Al_2(SO_4)_3$, 13 per cent	150	2.5	0
10 per cent $HgCl_2$	140	2.5	0.0196
10 " $FeCl_3$	140	2.5	0.0300
10 " NaCl	150	2.5	0.000024
10 " Ammonium Phosphate	140	2.5	0
10 " $Ca(OH)_2$	140	2.5	0.00019
H_2SO_3	70	...	0.000033

Excellent service in superheated steam.

[bh] Mean value 25 - 100° C.

[bi] Losses for this metal are in. penetration per month at 25° C., unagitated.

[bj] Other tests as follows:

Medium	Temperature, deg. Cent.	Velocity	Loss, in. penetration per month
15 per cent H_2SO_4	103	....	0.00072
25 " "	106	....	0.00058
50 " "	124	....	0.00022
10 per cent $FeSO_4$ + 1 per cent H_2SO_4	25	....	0.00068
" " " + " " "	70	....	0.00155
20 per cent " + " " "	25	....	0.00064
" " " + " " "	70	....	0.00199
Zinc Liquor (Lithopone manufacture)	90 - 95	....	0.00016
30° Baume Alum solution	B.P.	....	0.0006
50° " " "	B.P.	....	0
3 per cent HCl	70	....	0.00240
10 " HCl	70	....	0.00103
20 " HCl	70	....	0.0094
Conc. "	70	....	0.0374

[bk] Corrosion data on this line for Admiralty nickel annealed 825° C. and on line below for this same metal 10 numbers hard. Results are losses in mg. per sq. in. per day for test of 7¾ days duration, room temperature, unagitated.

[bl] Mean value 20 - 300° C.

[bm] Numerical data are for unagitated solutions in diffused daylight. First line contains tests at 20 - 30° C., second line, tests at 70 - 75° C. All losses are mg. per sq. in, per month. Other data follows:

		Loss
10 per cent H_3PO_4	20 - 30° C.	0.26
25 " "	"	0.13
85 " "	"	0.04
10 " "	70 - 75° C.	21.0
25 " "	"	7.1
85 " "	"	4.1

[bn] See note [bk].

[bo] Absence of salts.

[bp] Corrosion data on this steel are for samples oil quenched from 1850° F. and ground; half hour tests, room temperature without agitation. Interpreted as follows:
Excellent—No action.
Good—Surface tarnish; inappreciable solution.
Fair—Dissolved with very slow gas evolution.
Poor—Dissolved with gas evolution.

[bq] Tests of this material in unagitated unaerated solutions in diffused daylight. First line gives corrosion data for annealed material and second line for heat-treated material.

[br] Loss in weight in air as follows:

Temperature, deg. Fahr.	Time, hr.	Weight Loss, per cent	
		H. T.	An.
1420 - 1470	24	0	0
1470 - 1520	"	0.080	0.114
1540 - 1600	"	0.52	....

[bs] Mean value 25 - 300° C.

[bt] Bleaching solutions.

[bu] Corrosion data on this alloy is mg. loss per sq. in. per month at room temperature. Other data follows:

Reagent	Loss in mg. per sq. in. per mo.	
	No. 90	No. 92
4 per cent lactic acid	16.4	6.8
4 per cent citric "	13.4	12.1
25 per cent H_2SO_4, (158° F.)	36.5	42.5
20 per cent NaCl	2.2	1.5
25 per cent $CaCl_2$	0	2.7
10 per cent Alum	9.5	11.1
Sat. Sol. $Ca(ClO)_2$	13.9	14.6
Dry SO_2	0	0
H_2SO_3	6.8	18.4
Dry Cl	6.2	1.2

generally manufactured may represent only a few of the possible useful combinations within the range of the patent. Obviously this condition is quite natural and special materials of a given class are frequently available where consultation develops that specific problems require their employment.

Other than the actual collection and tabulation of the data, this presentation does not represent work done by or through the committee, except perhaps for such minor operations as the transposition of numerical data from one set of units to another. The facts recorded are those provided by the producers of each material. Practically all of the information furnished has been listed, except in those few cases in which comments were very apparently transcribed onto the questionnaire sheets in error, or in which such indefiniteness existed as to make tabulation impossible.

The compilation of the data on the resistance offered to corroding media presented particular difficulty. Information concerning the attack by the most common acids and alkalies was originally requested for 0.5-per-cent, 20-per-cent and concentrated solutions. Data submitted in quantitative and hence the most valuable form were not always available in the first two specific concentrations. The headings in the tables were therefore changed to "Very Dilute" and "Moderate Dilution" as being somewhat more representative, and the actual concentrations given with the respective weight losses or penetration values. In all but a very few cases, qualitative comments were the same for both dilutions so that the change of headings is in no way apt to be misleading. But in those few instances where differences in behavior are recorded for these first two columns of each group of three, the manner in which the data were requested must be borne in mind.

Very few took notice of the request to record, in the submission of qualitative corrosion data, their understanding of the terms "Excellent," "Good," "Fair," and "Poor," which were suggested as a uniform medium of expressing opinion on these matters. In fact in some cases other expressions than the above were employed, and it was necessary to convert them to one of the four preferred terms as well as could be done. This was accomplished by using as a criterion the following definitions which were the only detailed ones submitted and which are truly representative of the thoughts that originally dictated the preparation of the questionnaire:

Excellent.—Resistance to corrosion of such a degree in laboratory and service tests that a long life of years is obtained.

Good.—Resistance to corrosion of such a degree in laboratory and service tests that commercially long life is obtained.

Fair.—Resistance to corrosion of such a degree in laboratory and service tests that the material may be used where cost is not a consideration.

Poor.—Resistance to corrosion of such a degree in laboratory and service tests that the material is useless.

The only possible difference of opinion to record in respect to these definitions is a change under "Excellent" from "long life of years" to "practically unlimited life."

With reference to the mechanical properties of the various metals, there has been given in many cases a range of values resulting from thermal or mechanical treatment. In each case this fact has been indicated in the notes. In some cases the range given may represent merely a single series of tests, and in others the normal range of properties as determined over a long period of production. The former applies, of course, more particularly to the newer alloys, but such values as are given are believed to be fully representative. Where single values are quoted, they may be assumed to be normal minimum properties, where no statement to the contrary has been included. All of the data submitted on properties at elevated temperatures represent, of course, the results of single series of tests and must be given the weight that such observations warrant. Unfortunately, the speed of testing is not available for all of these determinations and as this speed markedly affects the results at the higher temperatures, such data require care in interpretation.

In spite of the above limitations and defects it is hoped and believed that these tables will serve a useful purpose, first, in aiding the engineer and purchaser in the selection of materials for difficult and severe service, and second, in establishing a milestone from which to measure future progress in these arts.

Submitted on behalf of the committee,

JEROME STRAUSS,
Chairman.

[The Committee on Papers and Publications wishes to express its appreciation of the valuable services that the above committee has rendered in arranging the Symposium and especially in compiling the data given in the tables accompanying this Introduction.—ED.]

CORROSION-RESISTANT ALLOYS—PAST, PRESENT AND FUTURE—WITH SUGGESTIONS AS TO FUTURE TREND

By P. A. E. Armstrong[1]

Corrosion-resisting metals of the past were non-ferrous. Bronze and copper alloys generally antedated ferrous alloys; of recent years, however, evidence has been obtained which demonstrates that iron and steel were known many years prior to their generally supposed date of origin. In the early days there was no question that copper alloys were very much more largely used than iron or steel; presumably the cost and difficulties attached to reducing iron ore were practically insurmountable. The early Egyptians seem to have used iron for personal adornment. Whether or not cutting tools such as hand chisels were made from iron and steel at this time has not been definitely decided. But it does seem highly probable from what we know of bronzes to-day that steel tools were available.

Among the earlier copper-base alloys, the following may be cited as representative:

	Copper, per cent	Tin, per cent	Lead, per cent	Iron, per cent
Celtic vessels	88.0	12.0	....	...
Bronze nails	95.1	4.9	....	...
Bronze (Troy, 1200 B.C.)	90.7	8.6	....	...
Bronze (Troy, 1200 B.C.)	93.8	5.7	....	...
Roman sword blade	91.4	8.4	....	...
Coin of Ptolemy IX	84.2	15.6	....	...
Athenian coin	89.4	9.9	....	...
Coin of Alexander the Great	86.7	13.2	....	...
Axe-head	88.0	11.2	0.8	...
Attic coin	88.5	10.0	1.1	...
Coin of Julius Cæsar	79.1	8.0	12.8	...
Roman axe (500 B.C.)	69.7	7.2	21.8	0.5
Sword blade	89.5	10.0	....	0.4
Egyptian statue	81.2	2.5	16.0	...
Egyptian statuette Osiris (300–200 B.C.)	76.8	11.2	11.7	...
Greek statue, fifth century B.C	84.5	9.5	5.3	...
Greek statue, fourth century B.C	89.0	6.1	4.9	...
Greek vase, fourth century B.C	81.7	10.9	5.3	0.1
Roman statue	78.3	10.8	10.2	0.1
Roman statuette	78.8	9.0	12.1	0.1

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[1] Vice-President, Ludlum Steel Co., Watervliet, N. Y.

These do not differ very largely from the alloys of to-day except that zinc did not seem to be a prevailing component, tin being the principal element alloyed with copper.

Excellent non-corrosive bronzes have been made embracing a variety of special alloys such as manganese bronze, aluminum bronze, phosphor bronze, etc. The nickel-copper alloy marketed under the name of monel metal is a very good example of a practical non-corrosive, non-ferrous metal.

The aluminum family is comparatively a modern development; some very excellent alloys contain aluminum and zinc and also aluminum, copper and zinc. They are very resistant to corrosion of some types. The widespread use of these alloys is a complete demonstration of their utility and value to the metal trade.

Condenser tubes have been the subject of extensive investigation and undoubtedly corrosion of condenser tubes is a very serious matter. Bengough in his various reports to the British Institute of Metals has thrown a great deal of light upon the causes of corrosion in condenser tubes. His suggestions as to improvement in the non-ferrous alloys used for this purpose have doubtless had a very marked effect upon the successful production of present-day material.

During the last few years there has been a determined effort on the part of the non-ferrous industry to popularize the use of copper and zinc for structural purposes, roof covering, etc., so that these two very valuable metals are coming into a great deal of prominence for installations of this character. Nickel does not seem to have been used as largely as its properties would warrant. Prior to 1914 quite a number of cooking utensils were made of chemically pure nickel. Since that time there has been a determined endeavor to use substantially pure nickel for applications of this character, but there seems to be some peculiar difficulty attached to successful manufacture.

But producers of non-ferrous metals are about to experience a competition they have not had to face before. Reference is made to the rustless irons which are now upon the market in a large variety of types. Cost will be the governing factor as to whether the rustless iron industry will develop at the expense of the non-ferrous industry or whether the non-ferrous industry will win out over the rustless iron. So much has been done and so wide is the knowledge of just what can be expected from brasses and bronzes that there appears to be no good purpose served by attempting to cover the high spots of investigations that have been conducted for a large number of years past. It seems more pertinent to cover, as completely as space will allow, the results of both early and recent investigators in the field of rustless iron.

The literature on the corrosion of iron is very large. Although much has been written on the subject, it has been principally on low-carbon iron with or without very slight additions of other metals such as copper. Iron of this character may be rust-resisting but it is not in any way rustless, so that this résumé need not enter this phase of rust and corrosion-resisting irons.

Irons with high percentage of chromium are the typical rustless irons. Their history is quite old. Berthier[1] in 1821 gives some very interesting facts concerning chromium and iron. He, however, worked with high-carbon chromium. He noticed that the higher the chromium content of his steels the greater their resistance to corrosion. Much has been said in these later days concerning the value of heat treatment but, providing sufficient chromium is present, heat treatment has little or no effect upon the non-corrosive properties of chromium irons. Before the British Association of Advanced Science, in 1838, there was presented a very interesting paper which showed that chromium-iron alloys or chromium steels are very resistant to corrosion by oxidizing agents, much more so than other alloys tested. Boussingault[2] recorded experiences with chromium steels containing about 4 per cent of chromium, and noted that higher chromium steels are not readily acted upon by nitric acid. He made the very important observation that the tightly adhering scale of chromium steels was such that when heated and quenched in water, the steel did not strip itself of scale and it was necessary to remove this scale by a file or some other abrasive to observe the temper color when tempering. Boussingault calls Berthier the inventor of chromium steels. It seems, however, that Boussingault overlooked the interesting article before the British Association of Advanced Science in 1838.

Woods and Clark, in a British provisional specification in 1872 (No. 1923), give very complete instructions for the manufacture of the present day rustless steel. These instructions are very clear to a metallurgist and without quoting the specification verbatim, the information is about as follows: For all ordinary purposes use about 5 per cent of chromium with a small addition of tungsten with medium carbon; for purposes where maximum resistance to corrosion is required, or acid resistance, use a 30-per-cent chromium steel with about 1.5 per cent of tungsten. The higher chromium content alloy is particularly useful for cutlery, drawing instruments, coinage metal and metal mirrors. The last part of their specification states that the proportions can be varied considerably in practice, meaning presumably between the upper and lower limit of the specification. It seems fair to assume that the higher content chromium alloy was to be used for purposes where maximum resistance to corrosion, rust, etc., was required; if the conditions were not quite so severe, somewhere between the 30 per cent of chromium and 5 per cent of chromium could be used.

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[1] *Annales de Chemie.*

[2] Iron and Steel Institute, 1886.

These two inventors who, it is believed, were the first to give practical information on the limits of composition of rustless and stainless chromium iron and steel, styled themselves in the specification as chemist and engineer. Our knowledge of present-day rustless steels does not go very much further than the disclosure of these two men. Robert A. Hadfield, now Sir Robert Hadfield, in 1892, in his classic contribution on chromium steels, stated that such steels with 9 per cent of chromium were attacked by sulfuric acid. This is not a contradiction of the former statement but merely shows that chromium steels are attacked by sulfuric acid, which is known to-day to be a fact.

The Holtzer Exhibit at the Paris Exposition of 1900 was extremely interesting from the point of view of the range of analyses and physical properties in the annealed, hardened and drawn condition. These analyses are right in the range of present-day rustless steel and cover the so-called stainless steels. It is perhaps fair to say that their non-rusting and acid-resisting properties must have been observed, although apparently not chronicled; if they were not actually noted in the year 1900, which is open to doubt, then they certainly were in the year 1904. For in this year appeared Guillet's article in *Le Genie Civil*, covering a large number of steels of somewhat the same analysis as those of the Holtzer Exhibit. This author discussed the alloys from a metallographic point of view and noted that the alloy of a composition similar to that of present rustless steels could not be etched in nitric and picric acids; he was forced to other acids such as hydrochloric acid to affect them. The samples used were annealed and hardened.

British patent No. 23,861, issued to La Societe Anonyme la Neo-Metallurgie in 1903, is for a rustless medium-carbon steel. The inventors in this instance used iron, nickel and chromium; iron between 16 and 38 per cent, nickel from 5 to 60 per cent, and chromium 24 to 57 per cent. A whole list of alloys are given, the chromium content ranging from 24 to 57 per cent. The following is quoted from this patent:

> " But the most important modification to which these elements, nickel and chromium, give rise consists in the important property (which forms the subject of researches of metallurgists at the present time) which they communicate to the said products, steels and irons, of presenting great resistance to corrosion.
>
> " This quality adapts them for a number of purposes and uses for which irons containing carbon and manganese in greater or less proportions are only very imperfectly adapted by reason of their liability to corrosion which is attributed to a great extent to the manganese which they contain. "

These alloys, as known to-day, are very rust-resisting and representative of very good rustless iron and steel.

Elwood Haynes, in U. S. Patent No. 873,745 (1907), described the discovery of an alloy which is quite rustless and can be used for a large variety of purposes. He again used chromium. The chromium content varied from 10 to 60 per cent, the remainder being cobalt, which metal is in the same chemical group as iron. He stated that his alloy should be carbon free, presumably meaning substantially carbon free. He further stated that carbon in the alloy caused tarnishing, which of course means high carbon. This effect of carbon had been previously noted.

The German patent to Borcher (No. 246,035, of 1910) and the article by Monnartz in *Metallurgie* in 1911, should be read together, since the Borcher patent is by Borcher and Monnartz and the Monnartz article covers the investigation out of which the patent grew. It was here affirmed that the alloys of chromium and iron with carbon in varying proportions had been very carefully studied by a large number of investigators and that the literature was full of contradictions. However, a careful analysis of these contradictions led to the conclusion that prior investigators had generalized a little too much, but that their actual findings were very true concerning these materials. A study of the facts actually developed, demonstrated that there is a very good history available as to the performance of chromium-iron alloys under attack by various acids and that there was no real contradiction. The earlier workers had tested with first one acid and then another and where an investigator had tested the material with sulfuric acid, he reported that chromium did not add to resistance to corrosion; when tested with other acids, resistance to corrosion was either more marked or less marked.

Very little information was available as to the behavior of chromium-iron alloys substantially free from carbon when tested with nitric acid. As previously noted, Guillet, in 1904, stated that dilute nitric acid had practically no effect upon chromium steel with various carbon contents including low carbon. Monnartz described in great detail his work on the preparation of the alloys so as to get them practically carbon-free. It does not seem probable they were actually able to produce alloys absolutely free from carbon. From what is known to-day of the tremendous affinity of chromium for carbon the alloys probably contained 0.10 or 0.15 per cent of carbon; the Borcher patent indicates that they must have contained this small amount of carbon in a statement to the effect that it is preferred to use carbon-free alloys or those containing low carbon. These researches show that up to 4 per cent of chromium with a low carbon content, the alloys are not very resistant to nitric acid, in fact as the chromium increases up to 4 per cent there is an increased attack by nitric acid. Above 4 per cent and up to 20 per cent chromium (with the greatest rate of increase in resistance occurring between 4 and 14 per cent) the attack is less, so that at about 20 per cent there is practically no attack at all by the concentrated or the dilute acid. Higher percentages of chromium are unnecessary unless the dilute nitric acid contains chlorine arising from an admixture of common salt. Samples containing about 20 per cent and more of chromium were submitted to corrosion tests in tap water, river water and sea water and it was found that the 20-per-cent alloy was extremely rust-resisting; higher percentages of chromium offered complete resistance to the action of sea water. Monnartz's general statement concerning these tests conveys the impression that they follow somewhat along the same lines as his nitric acid test; the higher the chromium content the greater the resistance to rusting.

In a second article the same author opens with a discussion of the effect of carbon on chromium-iron alloys but gives this up for the value of molybdenum in conjunction with chromium and iron. A small quantity of molybdenum with chromium seems to carry with it a very much greater power of resisting acid attack, rust, etc., than did an equivalent additional amount by weight of chromium. This was quite new and a patent was applied for on this alloy; this is the German Borcher and Monnartz patent of 1910. It was here stated that it was well known that chromium and iron combined in varying proportions were resistant to acid attack and to general corrosion and that no claim was made as to the novelty of this but only in respect to the addition of molybdenum to the combination. The patent covered an iron alloy, low in carbon, which has a high chemical resistance with good mechanical workability, and containing more than 10 per cent of chromium and some molybdenum. It was claimed that the molybdenum could be replaced by vanadium or titanium. A specific claim was for an alloy of 60 per cent chromium and 2 to 3 per cent molybdenum. Nothing was stated as to the value of heat treatment. With low carbon there can be no variation in rust-resisting value with heat treatment, particularly when the chromium is more than 10 per cent.

British patent No. 11,063, issued to Kuehnrich in 1911, is interesting, not so much from the point of view of the corrosion-resistance value of chromium, but from its value in combination with high carbon as a tool steel. However, the patent contains the statement that chromium steels with carbon up to about 1.5 per cent and more than 8 per cent of chromium are extremely well known.

J. Newton Friend in his "Corrosion of Iron and Steel," published in 1911, refers to alloys of chromium and iron as being less corrodible than iron, and cites the Hadfield alloy of 0.71 per cent carbon and 9.18 per cent chromium. Friend's book is full of very useful information on the rust-resisting properties of the lower-chromium iron alloys, which undoubtedly have a very big future, particularly when chromium to the extent of about 5 per cent is alloyed with other elements. There is a growing demand for an alloy that is extremely rust-resisting, such as rustless irons and steels of to-day, and also for another alloy that is not as rust-resisting as these metals but still very much more resistant than ordinary iron, whether it contains copper or not. It is interesting to note that the work of Friend, reported in 1911, and the present tendency were seen by the earlier investigators, Woods and Clark, in 1872. These two men were apparently much before their time.

In 1910 and 1911 there appeared a number of other articles dealing with chromium-iron-carbon alloys, giving the result of investigations as to their physical properties and researches on carbide isolation. The paper by Arnold and Read in the Iron and Steel Institute, 1911, is well worth careful perusal.

In 1912, a British patent was granted to the British Thompson-Houston Co., No. 15,342, for lead-in wires for glass bulbs for electric lamps. It was stated that the oxide formed on the surface of the high chromium wire was very thin indeed and that it welded nicely with the glass. Here was a recognition of the heat-resisting properties of high-chromium, low-carbon irons.

The Ludlum Steel Co., Watervliet, N. Y., in 1912 made a number of steels, containing about 16 per cent of chromium, with medium and high carbon, as commercial steels for various non-corroding purposes. Difficulties of manufacture were encountered. It was found that the alloys were very difficult to roll without seaming badly. But it was noted at that time that they were extremely rust-resisting.

The United States patent 1,026,461, issued to Schilling in 1912, was for chromium steel with about 9 per cent chromium, 3 per cent molybdenum, and about 1 per cent carbon. It was to be employed as safe or vault steel and it was claimed that it could not be melted by the oxy-acetylene flame.

About 1913, United States patent No. 1,057,754 was granted to A. L. Marsh for electrical resistance elements, to contain chromium between 20 and 35 per cent or more, with the balance iron. The patentee stated that it draws very well into wire and withstands high temperatures without oxidation; he recommends it for use in general electrical heating appliances and for other electrical purposes where resistance to oxidation at high temperatures is required. There is an earlier Marsh patent which has come into a great deal of prominence, covering the so-called Nichrome alloy. This is high-chromium nickel-chromium-iron alloy.

The British patents Nos. 13,414 and 13,415, of 1913, issued to Pasel are particularly instructive. (The two patents are the same as U. S. patents Nos. 1,404,907, 1,404,908 and 1,316,817 issued to Benno Strauss.) They cover alloys of chromium, nickel and iron, with a chromium content of from 7 to 25 per cent, nickel from 0.5 up to 20 per cent, and carbon from zero up to 1 per cent. It is stated that these alloys remain bright even when subjected to damp air for a period of months. Heat treatment is recommended and it is shown that some of these alloys are naturally austenitic or partly so and if quenched they should be drawn later to give hardness. This is obvious as the heat treatment puts them in a truly austenitic condition and drawing is the only manipulation that will change the austenite so as to produce a substantially hard condition. Pasel apparently had some difficulty in getting British patent No. 13,415 as he entered a disclaimer to the effect that the resistance of these alloys to concentrated acids or extremely strong acids was well known. In view of the earlier patents and the work of earlier investigators, it is clear that Pasel, to get a patent, was obligated to use another element with chromium and iron. The field for patenting was apparently changed from a binary alloy of chromium and iron to a ternary alloy of chromium, iron and another element (carbon excluded).

The British Pasel patents are for practically the same subject matter as Benno Strauss' patents in the United States. They all emanate from the same inventor and the British Pasel patents have been reviewed in preference to the United States patents because the former have an earlier date.

The Journal of the Iron and Steel Institute, for 1913, contains a paper by Friend, Bently and West on "The Corrodibility of Nickel, Chromium, and Nickel-Chromium Steels" that is extremely interesting from the point of view of the lower chromium contents, that is about 5 per cent. Friend, Bently and West's paper, taken in conjunction with the Pasel patents, throws considerable light upon what may be expected from these alloys with both high and low chromium content. It is to be noted that the Pasel patent does not go lower than 7 per cent of chromium and the Friend, Bently and West article does not go higher than about 5 to 6 per cent of this element.

Another British patent to Pasel (No. 13,413, of 1913), is for steels containing 15 to 25 per cent of chromium; if nickel is added, less chromium is needed. As an instance, 36 per cent of nickel with iron requires only 5 to 10 per cent of chromium to develop great resistance to corrosion. This composition is very much in line with that of the early Marsh patent, only the material was to be employed for different purposes.

In 1913 a British patent was granted to Griesheim (No. 14,448) for an iron-chromium alloy containing 25 per cent chromium or more, low in carbon; he claimed that it was very resistant to the action of ozone.

Le Genie Civil, of August 22, 1914, contains a very interesting article on nickel-chromium steels. An alloy of chromium, nickel and iron was stated to be hard and not affected by oxygen, to take a very fine polish, was non-magnetic, and was used for the manufacture of writing pens, fruit knives and jewelry settings. This is clearly the same material as that covered by the Pasel patent aforementioned.

United States Patent No. 1,150,113, granted to Haynes on August 17, 1915, was for an iron alloy containing cobalt and chromium; the cobalt to be not over 5 per cent and the chromium between 20 and 25 per cent with carbon under 1 per cent, preferably 0.60 per cent. He recommended this alloy for all purposes where rust-resisting properties were of importance, but particularly for cutting tools. This patent to Haynes was filed five days after another patent by the same man (No. 1,299,404), which was for chromium-iron alloys, containing chromium from 8 to 60 per cent, with carbon over 0.10 and under 1 per cent. He stated that this alloy hardens when cooling from a forging temperature and associates its non-corroding properties with the fact that it hardens on normal cooling from a forging temperature. The alloy when annealed, according to the inventor, does not have these properties. This, of course, is not in accordance with the facts.

About the same time, Harry Brearley applied for a patent in this country (issued as United States patent No. 1,197,256). The original application was filed March 29, 1915, but was changed and re-filed March 6, 1916. The patent covers the so-called stainless steel, *i. e.* an alloy from 9 per cent to 16 per cent chromium, with carbon from zero up to 0.70 per cent and which is hardened and polished when used for cutlery and other edge tools. Just how Brearley was able to harden the alloy when it contained zero carbon is not stated. It is claimed in the patent that the alloy contains no carbides when heat treated. The information yielded by this patent is that low-chromium steel can be used with carbon sufficiently high to make the material rust and stain when annealed, but in which these undesirable properties are not present when the alloy is hardened. The patent covered a range in which this is true and a greater range in which this is not true.

These two patents are quite interesting in the light of the literature, as they are for chromium, iron and carbon combinations which early inventors in their patents had stated were old and they therefore made no claim to them. As a matter of fact, the disclosure of Woods and Clark in 1872 is for material for about the same purposes as the Brearley and Haynes patents, except that Woods and Clark laid no stress at all upon heat treatment and both the Brearley and Haynes patents cover heat treatment, in one form or another, as being an essential accompaniment to the alloy to produce stain-resisting and rust-resisting characteristics. The work of Monnartz in 1911, and particularly his river water, tap water, and salt water tests, dealt with alloys within the range of the Brearley and Haynes patents, but the work of Monnartz did not disclose the benefits due to heat treatment.

Much credit should be given to Brearley for the commercial development of the so-called "stainless steel." His energy in bringing these types of steel into public notice has created a very creditable development.

Since 1915 there have been a large number of other patents issued for alloys of chromium and iron with various other elements. The Armstrong patent of 1919, (United States patent No. 1,322,511) was for silicon, chromium and iron combinations with varying carbon proportions. The value of heat treatment in this instance was brought out and also the fact that some of the alloys do not require such manipulation to make them stainless and rust-resisting. The scale-resisting properties at high temperatures were fully dealt with in this patent. Where carbon is employed with chromium and iron, with or without additional elements, if those elements which impart the rust and acid-resisting properties to the iron are not in sufficient abundance in the alloy, and carbon is employed, it is essential that the carbides which are the nuclei for attack, should be held in solution or in the ground mass of the alloy so as not to be the starting point for attack. This can only be accomplished by heat treatment.

Monypenny, in his paper before the Institute of Mining and Metallurgical Engineers in February, of this year, showed that if carbon in chromium-iron alloys is sufficiently low, heat treatment to impart rustless or stainless properties has little or no effect. This is in accordance, it is believed, with the results obtained by those who have investigated the subject.

Attention should be called to Bulletin No. 6 of the Coal Mining Investigations of the U. S. Bureau of Mines, published by the Carnegie Institute of Technology in 1923. The results of the electrolytic corrosion tests of various metals (including a wide variety of iron, nickel, copper and aluminum alloys) demonstrate the following facts for the solutions used:

1. A low-carbon chromium alloy possesses resistance to corrosion equal to pure lead; the weight loss for the two materials is less than that for any others.
2. With the same silicon, but higher chromium and carbon content, the loss is greater, due undoubtedly to the higher carbon.
3. A cast nickel-chromium-tungsten alloy and a low-carbon iron alloy containing high nickel and chromium with some molybdenum showed losses far greater than the above chromium-silicon steels.
4. A very high chromium, low-carbon and low-silicon steel shows a loss higher than the steels under (1). This may be ascribed to the low silicon or perhaps to oxides, if the steel was made by addition of chromium through the reduction of its oxide in the steel-making furnace.
5. Tests of nickel-chromium-silicon steels show clearly the effect of increasing the nickel content when the chromium percentage is close to 10.

Correlation of these accelerated tests with service tests of the same materials in mine waters show fairly close agreement.

An effort has been made to keep the various investigations and patents in chronological order. However, attention should be given to a paper read in 1915 by Mr. Leslie Aitchison of Sheffield, entitled "Experiments on the Influence of Composition upon Corrosion of Steel." This paper is most instructive as it deals with alloys of iron with various other elements besides chromium. It should be very carefully studied by those desirous of developing rustless irons as undoubtedly the chromium and iron combinations of our forebears is not the only solution to this problem. It is possible to produce iron alloys containing no chromium at all, which are both rustless and stainless and withstand acid attack in a manner superior to such metals, but again this is not true of all acids; rather is it true of a number of commercial acids. For instance, sulfuric and hydrochloric acids attack chromium alloys very actively, but when iron is alloyed with certain elements other than chromium, the resultant metals may possess tremendous resistance to those acids that easily attack chromium-iron alloys, namely sulfuric and hydrochloric acids.

One reason why the patent situation has been so carefully reviewed in addition to the technical articles is because patent applications are just as important to the metallurgist as a technical article and they are in themselves technical articles. The patent law calls for a disclosure sufficiently adequate so that a person skilled in the art has a full understanding of the invention and a written and pictured description, if necessary, of just how to produce the device, article or property that is disclosed in the invention. Therefore every patent is a technical article and those who are making researches in any field should carefully review the patent on the subject just as much as they do technical articles, and it was with this end in view that the paper has been devoted as much to patents on the subject as articles in the literature.

It appears that future demands will be for two classes of iron alloys, with a tremendous field open to each. One class will include materials that are rust-resisting and the other alloys that are practically rustless. The desirable characteristics of the second group seem to be possessed by those alloys that form a non-porous scale or oxide, so that although the surface may become rusty by having a bronze colored coating of probably a few thousandths of an inch thick, yet the rusting does not go further into the bar or sheet. Such alloys could be painted and the paint would not peel off due to rusting beneath it; they would undoubtedly fill a want for many structural purposes. Alloys that are truly rustless are finding a tremendous field in those installations where surface appearance and practically complete resistance to loss by corrosion, are important. As an instance of the first type of rustless steel, an alloy of 7 per cent chromium, 3 per cent nickel and 3 per cent silicon with carbon about 0.35 per cent is extremely rust-resisting, although the surface will rust; this rust, however, does not seem to penetrate the alloy. Bars of this analysis that were painted some four years ago are still in good condition. The paint, other than having changed color, shows no deterioration and no rust spots. Bars that have been used as fencing are now rusty but the rust cannot be wiped off by the hand and, when the surface of the bar is filed, the rust is about 0.002 to 0.003 in. thick. The rust seems to be non-porous so that the underlying metal has not suffered from continuous atmospheric attack. If the surface is ground clean and exposure continued, the metal merely takes on another rust film and then further attack ceases. Such an alloy is inexpensive compared with one containing 12 per cent of chromium with very low carbon and the balance iron, or with greatly superior alloys containing 17 per cent of chromium combined with iron, with an added element such as silicon, molybdenum, or nickel.

Chromium-iron alloys with about 12 per cent of chromium, although extremely rust-resisting, are not nearly as non-corrosive and rust-resisting as are those containing 16 per cent chromium and more. The manufacture of 12 to 14-per-cent chromium steels with very low carbon, that is to say under 0.10 per cent, is almost as expensive as the production of an alloy containing about 17 per cent of chromium. It is true that there is 20 to 50 per cent more chromium present, but the grade of ferro-chromium that has to be used for alloys of this type is expensive because of the very low carbon content, and if a comparatively expensive alloy steel of this character is to be used, there is no object in saving a few cents by reducing the chromium to a point where the safety factor is too low, that is from a truly rustless material to one that is only substantially so.

Under these circumstances the author is convinced from his own researches and from the general trend at this time that the rustless irons of the future, if the chromium alloy type is adhered to, will contain about 17 per cent of chromium and an added element with iron. The added element may be silicon, nickel, molybdenum, or various other elements, all of which serve a very useful purpose.

If silicon is employed, the alloy is extremely easy to manufacture in the steel mill because of the tremendous ease with which this material can be rolled at temperatures at which the metal is black and the high temperature at which it can be rolled in the initial stages, that is, from ingots to blooms. Rolling steel into sheets by maintaining its temperature at 1600° F. and above is a very difficult task, but with material that can be rolled black, rolling into sheets is very greatly facilitated; that is the situation when silicon is added to chromium steels.

If molybdenum is employed, the workability of the chromium iron is not made easier and there is a greater tendency for the metal to seam, but the molybdenum adds materially to the acid-resisting properties of the alloy and undoubtedly high-chromium irons containing molybdenum will be used for special purposes.

If nickel is alloyed with chromium and iron the troubles arising from air-hardening, normally austenitic structure, and the resultant great difficulties in machinery, will hold back wide development, in spite of the usefulness of the alloy. If high chromium is employed, say 17 per cent, nickel is not of material advantage except where resistance to sulfuric acid is important. Then very high nickel contents must be used and with this large percentage of nickel, 17 per cent of chromium makes the alloy somewhat difficult to handle so that the large additions of nickel along with chromium may generally result in steels of medium chromium and high nickel content. From the point of view of cost there is no object in loading up the alloy with expensive nickel and thereby reducing the amount of chromium that is essential. Under these circumstances nickel-chromium steels will probably not be a strong competitor in the commercial field with 17 per cent chromium iron. Alloys of chromium and nickel with iron are greatly enhanced in value from a commercial point of view if silicon is added. The machineability is increased, likewise forgeability.

If manganese is employed with silicon, chromium and iron, there is a slight improvement in machineability but no increase, that the author has been able to see, in the non-corrosive properties.

Tungsten is very similar to molybdenum in its effect upon chromium-iron combinations.

Vanadium, as an addition to these metals, seems to have only one characteristic—it keeps the grain size small and this is a problem in all of the low-carbon high-chromium irons. Its added cost does not seem to warrant its use, as grain size can be controlled by pouring temperature and mechanical work.

Titanium and zirconium with chromium and iron are useful, but there are a number of mechanical difficulties attached to the use of both, so that these additions to rustless alloys will probably not be commerial for some time to come.

From this very sketchy outline of the effects of various elements upon chromium-iron alloys, the author believes that 17 per cent chromium alloyed with iron, along with silicon about 1.5 per cent, and carbon under 0.10 per cent, will be received with increasing favor by structural designers and probably will be the leader as the most effective rust-resisting iron of the future. The easy workability in the commercial steel mill is a factor that cannot be disregarded, and the ease with which it can be machined is a matter of tremendous importance to the fabricator.

The very high non-corrosive properties of the alloy are naturally of prime importance. The use of silicon-reduced ferro-chromium will enable the alloy to be made in the near future at lower cost than to-day. The metal is tough and of very excellent physical properties. Contrary to the generally recognized property of high-chromium irons, silicon-chromium irons increase in toughness as their temperature is raised.

The heat-resisting characteristics of chromium-silicon irons with low or high carbon are well recognized and put to extensive commercial application at this time, Examples are automobile valves, Diesel engine valves, and internal combustion engine valves generally; this grade of non-corrosive iron and steel is here used as standard equipment and from the present-day trend, it is believed that this alloy will be even more largely used than in the past. A few years ago, particularly during the war period, stainless steel was used for internal combustion engine valves. This valuable metal has now been superseded by the chromium-silicon steel because of the tremendously enhanced scale-resisting properties imparted to the chromium-iron alloy by silicon.

NON-RUSTING CHROMIUM-NICKEL STEELS

By B. Strauss[1]

Metallurgists for a long time past have been accustomed to alloy iron with nickel with a view to the improvement of the iron, whereas the discovery of the valuable properties of chromium is of comparatively recent date, since carbon-free chromium, in the shape of solid lumps, was first obtained by means of the alumino-thermic process evolved by Hans Goldschmidt, of Essen. Hittorf was the first to study the properties of chromium obtained in this way, and in 1898 he published a report entitled "On the Electromotive Behavior of Chromium." In this he says: "Pure water, on the contrary, is almost entirely without effect; when exposed to the air at low temperatures, chromium also retains its luster and does not become tarnished." In a further investigation, entitled "On the Passivity of Metals," Hittorf arrives at the conclusion that the passivity of the four metals chromium, iron, nickel, and cobalt, is due to a state of tension of the molecules, which arises under certain conditions and which is best retained by chromium.

In seeking for a suitable material from which to make protective tubes for thermo-electric couples, the author started on the supposition that it ought to be possible to make use of the valuable properties of chromium, that is, its resistance to the action of oxygen, for the purpose of increasing the resistance of iron against the attack of hot gases, in view of the fact that nickel had, shortly before, been rendered extremely heat-proof by the addition of about 10 to 15 per cent of chromium. In 1910, the author had the following five experimental alloys prepared:

	C 1	C 2	C 3	C 4	C 5
Carbon, per cent......	0.38	0.49	0.60	0.22	0.31
Silicon, "	0.01	0.02	0.02	0.07	0.08
Manganese, "	0.12	0.10	0.09	0.13	0.11
Nickel, "	0.10	0.10	0.10	1.75	5.00
Chromium, "	9.81	19.00	28.85	10.05	20.10

These steels had been forged into rods and were to be made into protective tubes for pyrometers. Of the above, the two alloys C 4 and C 5 containing a higher percentage of nickel, after having been subjected to a simple annealing operation at 800° C., turned out to be unworkable.

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[1] Fried. Krupp, A. G., Essen, Germany.

Polished specimens taken from the above bars, after having been exposed for some time to the atmosphere of the laboratory, revealed the curious fact that particularly those steels which contained 20 per cent of chromium had remained perfectly bright, while other bars, even those containing up to 25 per cent of nickel, had become rusty. As investigations were being carried out at the same time with regard to the corrosion of metals in fresh water and sea water, it was deemed expedient to extend this investigation to cover both chromium and chromium-nickel steels. As, however, only such alloys as could be put to practical uses were to be selected for the purpose, it became necessary to investigate the tensile strength of these alloys considered as a function of the heat treatment undergone by them. In connection with the study of the mechanical strength of the chromium-nickel steels, their structure and other physical properties were also looked into. This work was carried out by the author, in collaboration with Mr. Maurer, in the course of the years 1909–1912 in Messrs. Krupp's Physical Research Laboratory, the results being published in Krupp's Monthly Magazine for August, 1920.

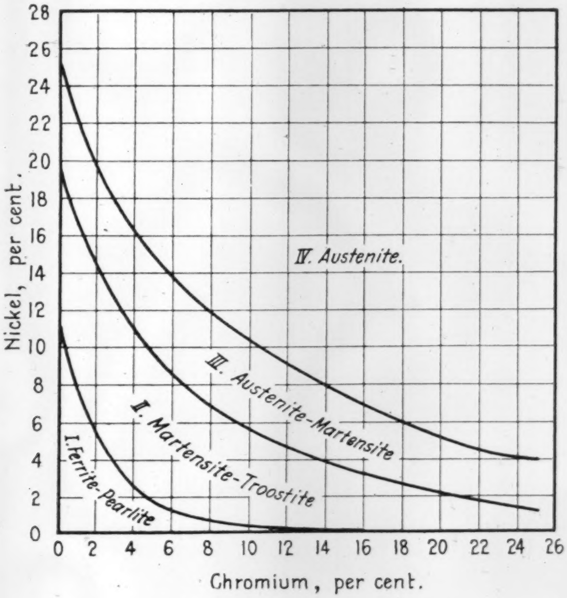

FIG. 1.—Diagram of Quaternary Chromium-Nickel Steels.

The structure of the forged rod C 4 revealed martensite, whereas the steel C 5 in the forged state, consisting of grains having enclosures of carbide, must be regarded as inclining towards austenite. The mechanical test values for the above two high-chromium-nickel steels are as follows:

	C 4	C 5
Tensile Strength, kg. per sq. mm.	152	80.3
(lb. per sq. in.)	(216,000)	(114,000)
Elongation, per cent	5.3	7.3
Brinell Hardness	393	279

The temperature curves of C 4 showed the Ac point to be at 780° C. and the Ar point at 280° C. It was found that by annealing at a temperature below the Ac point, the martensite could be changed into troostite. The mechanical test results obtained with this material after oil-hardening are:

	C 4, OIL-HARDENED AT 900/550° C.	C 4, OIL-HARDENED AT 900/700° C.
Yield Point, kg. per sq. mm.	84	52
(lb. per sq. in.)	(119,000)	(74,000)
Tensile Strength, kg. per sq. mm.	95	74
(lb. per sq. in.)	(135,000)	(105,000)
Elongation, per cent	16.6	24.3
Reduction of Area, per cent	58	66
Brinell Hardness	269	219
Tenacity on Notched Bar, kgm. per sq. cm.	21.4	23.9
(ft-lb. per sq. in.)	(1000)	(1120)

The best heat treatment for the other chromium-nickel steel, C 5, was found to consist in quenching in oil or water at 1150 to 1200° C. By this means the steel was rendered very tough and completely non-magnetic. The mechanical test values found in this state are:

	C 5, QUENCHED AT 1150–1200° C.
Yield Point, kg. per sq. mm.	35
(lb. per sq. in.)	(49,700)
Tensile Strength, kg. per sq. mm.	82
(lb. per sq. in.)	(116,500)
Elongation, per cent	52
Brinell Hardness	200
Tenacity on Notched Bar, kgm. per sq. cm.	35
(ft-lb. per sq. in.)	(1630)

The diagram of chromium-nickel steels with low carbon content, as determined by us with the aid of numerous specimens, is represented in Fig. 1. According to this diagram, chromium-nickel steels may be divided into four groups: namely,

I. The ferrite-pearlite group,
II. The martensite-troostite group,
III. The austenite-martensite group,
IV. The austenite group.

Table I shows the results of corrosion tests made with a number of different iron alloys in comparison with the two brands of high-chromium-nickel steel that were first applied by Messrs. Krupp to practical uses. The first of these belongs to the martensite group designated by them as "VM" and the second to the austenite group designated as "VA." The composition of these two alloys is as follows:

	CARBON, PER CENT	CHROMIUM, PER CENT	NICKEL, PER CENT
V1M	0.15	14	1.8
V2A	0.25	20	7

TABLE I.—RESULTS OF CORROSION TESTS.

RUSTING THROUGH EXPOSURE TO AIR	LOSS IN WEIGHT
Ingot iron	100
Steel with 9 per cent Nickel	70
Steel with 25 per cent Nickel	11
V1M	0.4
V2A	0
CORROSION IN SEA WATER	
Ingot iron	100
Steel with 9 per cent Nickel	79
Steel with 25 per cent Nickel	55
V1M	5.2
V2A	0.6
CORROSION IN 10-PER-CENT NITRIC ACID SOLUTION, COLD	
Ingot iron	100
Steel with 5 per cent Nickel	97
Steel with 25 per cent Nickel	69
V2A	0
CORROSION IN 50-PER-CENT NITRIC ACID SOLUTION, BOILING	
Ingot iron	100
Steel with 5 per cent Nickel	98
Steel with 25 per cent Nickel	103
V2A	0

It followed from the examination of the structure, from the mechanical tests, and from the corrosion tests, that by suitable heat treatment of chromium-nickel steels high in chromium there are obtained two groups of quaternary iron alloys which, besides possessing great mechanical strength, are further distinguished by being absolutely rust-proof and acid-proof.

The first (VM) group of practical special steels, of martensitic structure, comprises those containing from 10 to 16 per cent of chromium, 0.5 to 4 per cent of nickel, and 0.1 to 0.6 per cent of carbon. When cooled in the ordinary manner, these steels are rather hard, being self-hardening. The carbon appears to be in solution, and the structure is very fine-grained and homogeneous. By annealing, martensite is converted into troostite, but the homogeneous structure (Fig. 2) remains. This is very essential from the point of view of resistance to corrosion, as in the case of non-homogeneous structures local elements from which corrosion starts are easily formed. For example, in examining the first surgical knives made from a steel containing 14 per cent chromium, 0.8 per cent nickel and 0.15 per cent carbon, the author found that in the hardened state they were very corrosion-resisting, but not hard enough. Endeavors to impart greater hardness to these knives by means of cementation in powdered coal were successful, but at the same time it was found that the knives then rusted very quickly in water containing air. Investigation revealed the presence of free carbide, this having been the cause of the lack of homogeneity and the ease with which rust formed.

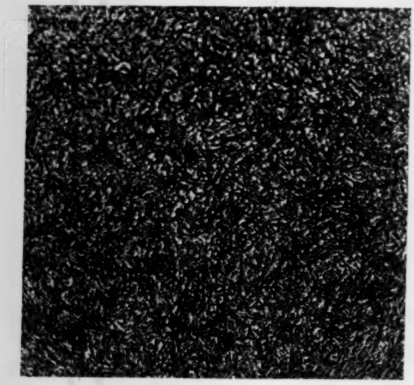

FIG. 2.—Troostitic Structure of an Annealed Chromium-Nickel Steel Containing 0.15 per cent Carbon, 14 per cent Chromium, 0.8 per cent Nickel (× 200).

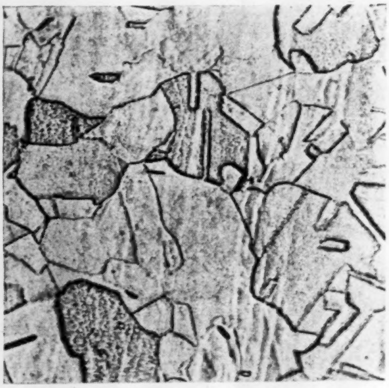

FIG. 3.—Austenitic Structure of a Chromium-Nickel Steel Containing 0.25 per cent Carbon, 20 per cent Chromium, 7 per cent Nickel (× 200).

The second (VA) group of chromium-nickel steels (of austenitic structure) comprises those containing from 20 to 25 per cent of chromium, 4 to 20 per cent of nickel, and 0.1 to 0.5 per cent of carbon. In the forged state, the structure of these steels shows a greater or smaller amount of carbide enclosures, according to the temperature at which the final forging was carried out, and also to the percentage of carbon. By heating to 1150 to 1250° C. and subsequent rapid cooling, this carbide is dissolved, and homogeneous austenite results (Fig. 3). This is the state in which these steels possess the greatest tenacity and resistance to corrosion.

In the austenite group also, the carbon content plays a certain part. A low carbon content increases resistance to corrosion. The carbon may, it is true, be dissolved by quenching the chromium-nickel steel at temperatures ranging from 1150 to 1250° C., but by annealing at 700° C. part of the carbide is again separated, especially at the boundaries of the grains, and is thus liable to exert an unfavorable influence on the mechanical strength of the material. Care should therefore be taken, when working this material at the higher temperatures, to carry out this high-temperature heat treatment as a final operation, in order to obtain a homogeneous structure. The effect of the separation of carbide taking place at the boundaries of the grains within the limits of temperature just mentioned may also be detected in the much lower elongation obtained in tension tests made at elevated temperatures with chromium-nickel steels of the austenite group having a slightly higher carbon content, say from 0.3 to 0.5 per cent. Fig. 4 shows the curve of elongation as a function of temperature, obtained in tension tests made at elevated temperatures with an austenitic chromium-nickel steel containing 0.45 per

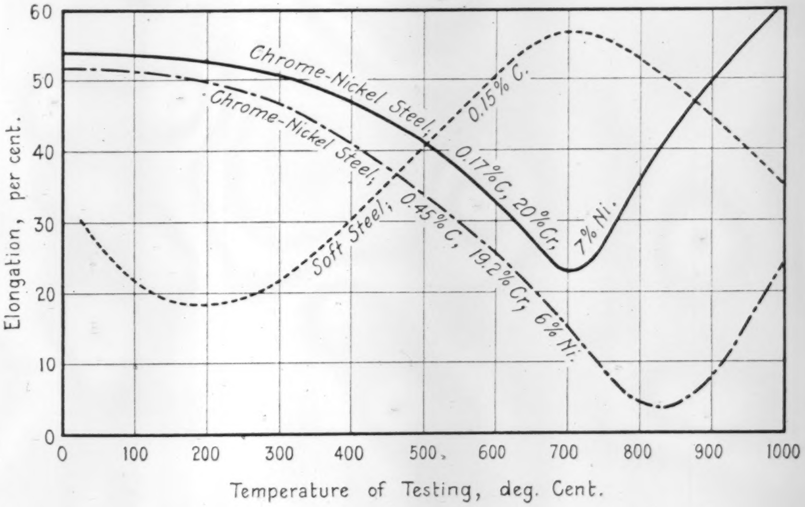

FIG. 4.—Change of Elongation with Temperature in Tests at Elevated Temperatures of Highly Alloyed Chromium-Nickel Steels and Soft Steel.

cent carbon, 19 per cent chromium, and 6 per cent nickel, and also with another chromium-nickel steel containing 0.17 per cent carbon, 20 per cent chromium, and 7 per cent nickel, in comparison with soft steel of 0.15 per cent carbon.

The different behavior in respect to expansion due to heat of a martensitic and an austenitic chromium-nickel steel, in comparison with ingot iron, is illustrated in Fig. 5.

The high resistance of the V2A brand of steel to the action of gases and vapors at high temperatures will appear from the following:

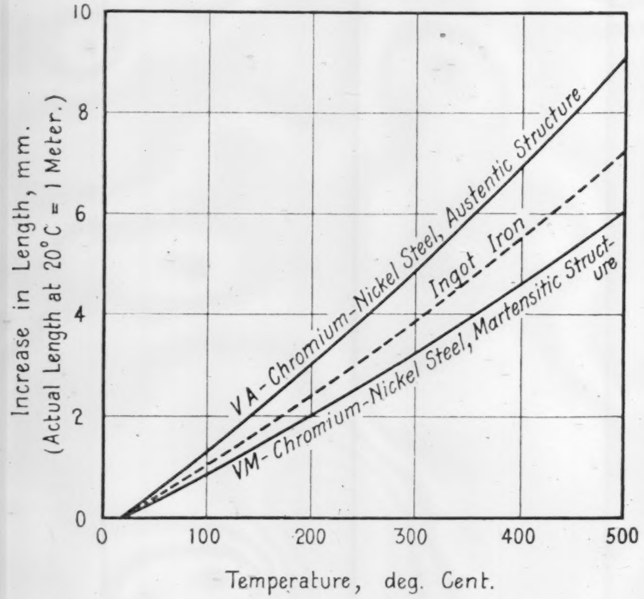

FIG. 5.—Thermal Expansion Curves of Chromium-Nickel Steels and Ingot Iron.

Specimens having a surface area of 168 sq. cm., heated to 1000° C. for 100 hours in a furnace, with admission of air, sustained a loss in weight of 416 g. in the case of ingot iron, as against 6 g. in the case of V2A steel.

In the autumn of 1912, patents were applied for by Messrs. Krupp for both groups of alloys, and they were soon afterward placed on the market. As far as the author is aware, these were the first rust-proof steels publicly advertised as such. Goods made from both groups were first shown at the Malmö Exhibition in April, 1914.

Applications

Rust-proof chromium-nickel steels of the martensite group can be used for parts of machines requiring great mechanical strength in conjunction with resistance to rusting and corrosion. Annealed low-carbon chromium-nickel steels, containing from 0.1 to 0.2 per cent carbon, 13 to 16 per cent chromium, and 0.5 to 2 per cent nickel are suitable for manufacturing steam turbine blades, gun barrels, shafts, piston rods, valve spindles, pump valves, etc. The tensile properties of these alloys lie approximately within the following limits:

Yield Point, kg. per sq. mm	45–70
(lb. per sq. in.)	(64,000–99,500)
Tensile Strength, kg. per sq. mm	65–90
(lb. per sq. in.)	(92,500–128,000)
Elongation, per cent	22–12

Chromium-nickel steels somewhat higher in carbon (from 0.3 to 0.5 per cent) and low in nickel are used in the hardened state for cutlery of all kinds, as table knives, razors, machine knives, scissors, saw blades, knife-edges for balances, ball and roller bearings, etc.

By far the wider range of application, however, belongs to the chromium-nickel steels of the austenite group. For machine parts, apparatus, utensils and articles of daily use which are subjected to chemical action and must be capable of effectively resisting corrosion, the V2A brand can be recommended and can also be considered as absolutely rust-proof in damp air. The tensile properties of V2A steel vary with the carbon content, and are contained within the following limits:

Yield Point, kg. per sq. mm	30–38
(lb. per sq. in.)	(42,500–54,000)
Tensile Strength, kg. per sq. mm	70–84
(lb. per sq. in.)	(99,500–119,000)
Elongation, per cent	54–48

At the same time, this material is extremely tough and offers very high resistance to mechanical wear and tear, being in the latter respect about equivalent to Hadfield's steel containing 12 per cent of manganese. As V2A steel contains iron exclusively in the gamma form, it is further perfectly non-magnetic.

Austenitic V2A steel is used for acid pumps, valves of all kinds, valve plates, valve seats, steam valve rings, steam trap valves, mud valves, plunger pistons, piston rods, shafts, beater blades, piping, kitchen utensils, spoons, forks, table utensils, beer casks, Hollander knives, knives for cutting glue, surgical and dental instruments, denture plates, metal mirrors, etc. Mirrors and other polished articles, when made of V2A steel, retain their polish permanently, whereas polished nickel becomes dim after a comparatively short lapse of time. Owing to its ductility, V2A steel permits of being rolled, forged, stamped and drawn out in the cold state, so that it can be made into thin sheets, strips, wire and wire gauze.

This brand is well adapted for a great variety of uses in the chemical industries, where it is called upon to resist the attack of nitric acid, ammonia, or hydrogen peroxide in the presence of steam (aqueous vapors). Its resistance to hot diluted sulfuric acid is not satisfactory, but if a few per cent of nitric acid be added to the solution, V2A steel becomes absolutely passive and is no longer attacked by the acid. V2A steel lends itself well to electric and autogenous welding, and can thus be worked into apparatus for chemical uses.

STAINLESS STEELS: THEIR HEAT TREATMENT AND RESISTANCE TO SEA-WATER CORROSION

By Jerome Strauss[1] and J. W. Talley[2]

Introduction

Metals to withstand the deteriorating influence of sea water and sea-water-laden atmosphere have always been in demand along the water fronts of coastal cities and for general naval service. Where protective coatings of paint or other impervious media could be employed (and renewed when necessary) ordinary low-priced structural steels satisfactorily filled most needs, but under severe conditions of exposure more permanent metals were required. Until about 1895, various copper alloys offered the only means of combating these conditions; at that time the high-nickel steels (20 to 40 per cent nickel) made their commercial appearance and later in 1905, monel metal was introduced to the industrial world. But the cost of these various alloys in the rolled form is still five to ten times that of simple carbon steels and, with the exception of monel metal, their resistance to destruction by sea water is far from perfect. The introduction, therefore, of iron alloys offering marked resistance to many corroding media and the prospects of early reduction of their cost to a nominal figure, was greeted by naval interests with much enthusiasm. The prophesied moderate price has not as yet been realized (although the past few months have witnessed sharp declines), and the early impression that all these new metals were immune to the attack of sea water has been short-lived; but in spite of these disappointments, they are finding a constantly widening sphere of application and meeting with a large measure of success. Extremely rapid introduction has been responsible for their employment for a few purposes for which they were ill-suited, and in many cases for the use of one composition where another was clearly indicated as most desirable. Such occurrences have frequently caused condemnation of any iron alloy classed as corrosion resistant. The same may be said of many ill-advised heat treatments. This, of course, is not new and has at times retarded the introduction of other metals ideally suited to specific applications.

The term "stainless steel," because of early employment of a particular iron-carbon-chromium alloy in cutlery manufacture, where it effectively resisted discoloration by fruit and vegetable juices, has come to be applied to one single composition—a steel of approximately 0.25 to 0.45 per cent carbon and 11 to 16 per cent chromium. But many new steels other than this particular alloy will remain bright under various conditions of corrosive attack, so that this limited application of the term is hardly justified. Even with the above limits of chromium content, alloys ranging from less than 0.10 to as high as 1.25 per cent carbon are employed where permanence is a requisite; and this is only one very narrow strip in the useful portion of the ternary diagram, to say nothing of the incorporation of alloying elements other than chromium, in small and large percentages. For the purpose of the present paper, therefore, the term "stainless steel" will be applied to all of the newer alloy steels possessing marked resistance to many deteriorating influences and the commercial stainless steels will be arbitrarily subdivided into three groups:

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I. "Hardenable" chromium steels.
II. Chromium steels that do not "harden."
III. Steels in which the predominating alloying element is nickel.

The division between groups I and II is not sharp but none of the alloys of group II, as considered here, can be hardened by heat treatment to much above 400 Brinell, and all of those of group I will harden to 500 Brinell or higher on thin sections. All of the alloys to be discussed are steels, so that iron is in every case the predominating component.

MATERIALS AND TESTING METHODS

The compositions of the steels used in the tests about to be described are given in Table I. Under the designation of "hardenable chromium steels," twelve analyses are listed. Steels A, B, and C are representative of the metal that is being used in cutlery and to which the term "stainless steel" has been generally applied. A steel of like composition, with the exception of a slightly higher carbon content (steel D) was manufactured extensively during the earlier period of "stainless steel" production in this country, probably largely because of raw material characteristics and manufacturing difficulties, but to some degree also to secure greater hardness in edge tools (probably cutting ability rather than "hardness"); present tonnage of this carbon content is not great. Steels E and F (and probably G also) were developed primarily for uses other than corrosion resistance, but have been included owing to their ability to resist the attack of sea water equally as well as other steels designed specifically for stainless qualities. Steels H to L are very special materials, suitable for edge tools other than cutlery, and possessing also resistance to abrasion in varying degree.

Among the softer chromium steels, M, M1 and M2 represent the product to which the term "stainless iron" has been applied, although the chromium content of M and M1 is somewhat above the average, and the accidental nickel of M rather large in amount. Steels N, O, and P are intermediate in composition, as to carbon content, between "stainless iron" (usually 0.12 per cent carbon or less) and the cutlery alloy. Steel Q is a very special metal, containing somewhat more chromium than any other "soft" alloy being marketed at the present time. Steel R, in addition to its high chromium, contains an intentional addition of copper, and steel S, developed for purposes other than corrosion resistance, has been introduced solely to note the effect of its tungsten and silicon content.

TABLE I.—CHEMICAL COMPOSITON OF VARIOUS STAINLESS STEELS.

All values are expressed in per cent.

	Steel	C	Si	S	P	Mn	Ni	Cr	V	Mo	Cu	W
Group I	A	0.32	0.12	0.025	0.013	0.21	0.21	13.96	0.04	....	....	....
	B	0.37	0.20	0.020	0.026	0.51	none	14.50	trace	....	....	....
	C	0.37	0.37	0.011	0.015	0.54	0.22	14.71	0.04	....	0.08	....
	D	0.53	0.53	0.026	0.019	0.41	0.11	13.36	0.04	....	....	....
	E	0.51	1.46	0.015	0.017	0.49	0.10	7.91	0.03	0.74		none
	F	0.51	2.86	0.010	0.013	0.34	none	8.66	0.25	none	0.10	....
	G	0.53	1.53	0.023	0.007	0.40	trace	6.78	none	none	....	7.49
	H	0.65	0.80	0.011	0.018	0.36	none	16.85	none	0.51	0.06	....
	I	0.76	1.10	0.009	0.021	0.36	none	12.09	0.04	none	0.06	....
	J	0.80	0.43	0.018	0.019	0.48	0.24	18.16	0.06	....	0.09	....
	K	1.12	1.05	0.010	0.048	0.40	trace	17.68	0.15	0.03	trace	none
	L	1.13	1.10	0.017	0.034	1.17	0.22	21.93	0.01	....	none	....
Group II	M	0.09	0.15	0.039	0.010	0.31	0.64	15.96	0.04	....	....	....
	M1	0.09	0.24	0.034	0.010	0.26	trace	15.26	trace	....	....	....
	M2	0.11	0.36	0.044	0.018	0.47	0.22	12.16	0.02	....	0.04	....
	N	0.18	0.39	0.018	0.014	0.29	none	12.90	none	....	0.06	....
	O	0.19	0.59	0.032	0.019	0.43	0.34	16.50	0.03	....	....	....
	P	0.18	0.98	0.011	0.015	0.21	0.08	15.84	0.03	none	0.35	....
	Q	0.64	0.47	0.034	0.020	0.66	none	27.21	none	....	....	....
	R	0.24	0.29	0.025	0.015	0.49	trace	20.44	0.02	....	1.08	....
	S	0.32	2.77	0.012	0.004	0.37	0.11	19.29	0.04	0.05	trace	2.54
Group III	T	0.63	0.32	0.020	0.032	1.15	26.35	0.06	....	....	0.27	....
	U	0.49	0.24	0.039	0.021	0.58	35.42	none	none	....	none	....
	V	0.68	0.28	0.032	0.019	0.52	27.60	2.17	none	....	none	....
	W	0.44	1.36	0.024	0.015	0.54	28.51	5.38	....	....	0.48	....
	X	0.46	1.67	0.016	0.012	0.66	22.70	7.31	....	....	1.12	....
	Y	0.39	1.07	0.013	0.006	0.37	20.91	7.57	none	....	0.04	....
	Z	0.35	2.45	0.024	0.022	0.69	25.80	16.85	....	....	0.08	....

The simple nickel steels are represented by steels T and U; these materials have frequently been manufactured with lower carbon percentage than in the present samples. Steel V was produced in this country prior to the discovery of the advantages of higher chromium additions, its 2 per cent of this element being used in conjunction with the carbon because of its beneficial effect on tensile properties, particularly the proportional limit. The remainder of the steels listed are representative of a group brought into prominence at about the same time as the hardenable chromium steels and combining many of the properties of the nickel steels with those in which chromium is the predominating alloying element.

The preparation of the materials and the methods of testing to be described are applicable to practically all of the experiments conducted. Where deviations from this procedure have occurred, special mention will be made. Bars for all tests were initially 1 in. in diameter. For the steels of group I, all bars were rough machined prior to heat treatment in order to permit finishing of the hardened members of any series by grinding; for purposes of obtaining comparable heat treatment effects for all members of each series, it was of course necessary to rough machine bars that would ultimately be "soft" to the same essential dimensions. Accordingly, prior to heat treatment, all test bars to be hardened and subsequently tempered to not over 1000° F. were machined to the form shown in Fig. 1 (*a*); for higher tempering temperatures, the specimen of Fig.

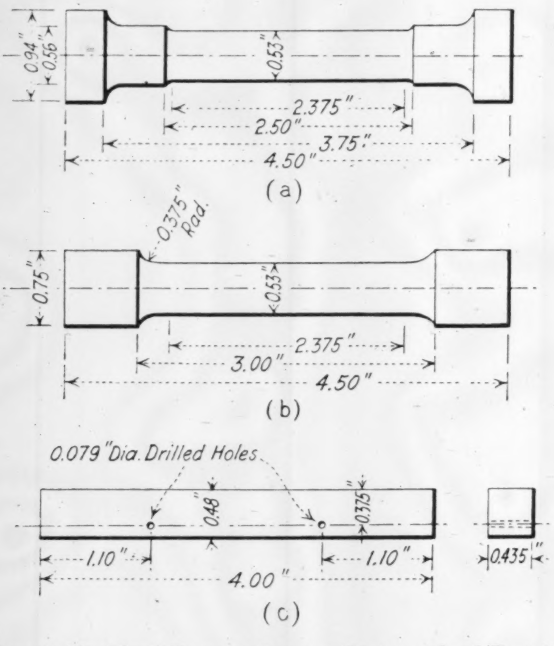


FIG. 1.—Rough Machined Bars for Tension Test and Izod Test Specimens.

1 (*b*) was used; all Izod bars were initially in accordance with Fig. 1 (*c*). After heat treatment, the tension test bar of Fig. 1 (*a*) was ground to 0.500 in. in the central portion, the bar of Fig. 1 (*b*) was ground to 0.500 in. in the central portion and threaded on the ends and the impact bar was ground to 0.394 in. square with the distance from the bottom of the hole to the back surface 0.315 in. The steels of groups II and III were heat treated as 1-in. diameter bars, test specimens then being machined from these to the finished forms just described.

All of the heat treatments, except tempering operations below 600° F. (which were done in an oil bath) were performed in electric furnaces, temperatures above 1600° F. being obtained in a carbon plate resistance unit. In the latter furnace a platinum and platinum-rhodium thermocouple was used and for other work base metal thermocouples, all carefully calibrated and connected to a potentiometer system. For annealing and quenching operations, test bars were charged cold into a furnace at the required temperature and after reaching that temperature, the latter was maintained constant for 30 minutes prior to cooling. Tempering was conducted in a similar manner but with the period of constant temperature extended to 60 minutes. In the quenching operation, pure sperm oil or water at 65 to 75° F. was employed.

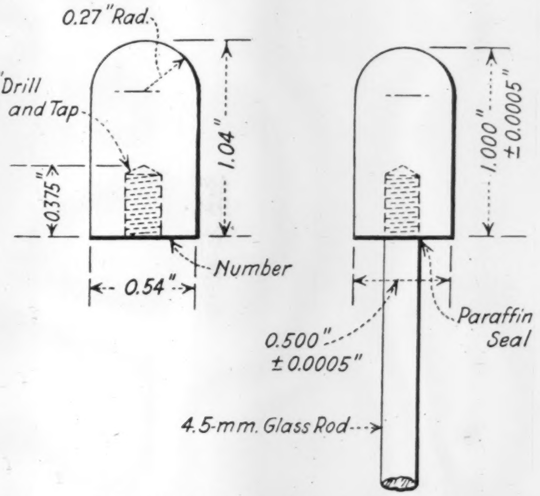


FIG. 2.—Rough and Finished Corrosion Specimens.

Proportional limits were obtained with a Ewing extensometer reading directly to 0.0002 in. and by interpolation to 0.00002 in.

The specimens for the corrosion test were small cylinders of the form shown in Fig. 2 and were prepared from $\frac{5}{8}$-in. round bars forged from the original 1-in. rounds. Before heat treatment, which was conducted in a manner similar to that described for the tension and Izod test bars, the specimens were slightly oversize as shown in Fig. 2 (*a*). After heat treatment, they were ground to the dimensions of Fig. 2 (*b*); these tolerances are not at all difficult to maintain in grinding, and adherence to them avoids any necessity for the computation of surface area in comparing weight losses. Grinding in all cases was so performed as to leave an extremely smooth surface, the markings on which, so far as observation with a 20-power hand glass could determine, was alike for all pieces.

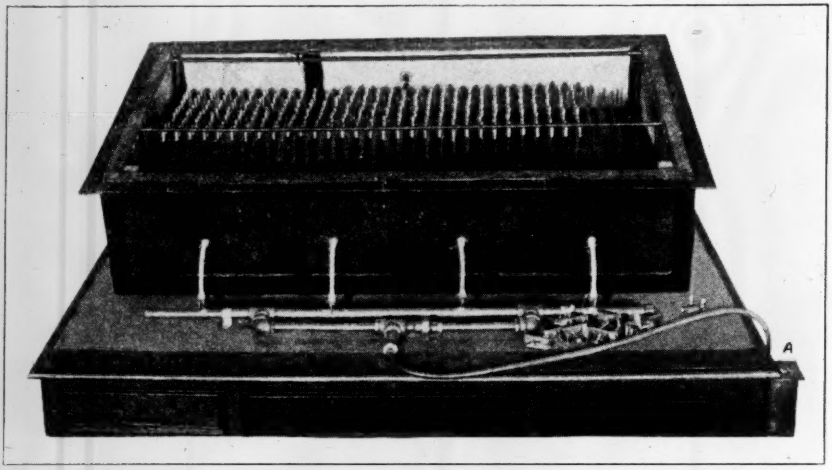


Fig. 3.—Testing Equipment.

The testing equipment used is illustrated in Fig. 3. Air at 17 lb. per sq. in., after passing through a column of water of about 15 in. in a brass tube, *A*, enters the box through the four adjustable monel metal aspirators. Inside the box, which is of alberene stone, two glass plates so deflect and break the spray as to insure uniform conditions in the mist surrounding and moving past each test piece. These test pieces are supported on glass rods resting in holes on a board impregnated with asphaltum; the suspensions for the board are monel metal. The box is covered with a clear glass plate when in operation so that the movement of the fog can be clearly traced and any operating difficulties quickly discovered.

The test pieces were cleaned in alcohol, weighed, then warmed slightly and a drop of paraffin placed in the hole; the glass rod was inserted, the excess paraffin carefully scraped away and the specimen then washed twice with benzol and once with alcohol and dried. Testing extended over a period of 500 "spray-hours," the actual spraying time being 17 hours for each working day; during the remainder of each day and on Sundays and holidays, the specimens remained in the moisture saturated atmosphere of the spray box. During the testing period the temperature varied from 60 to 78° F., with a mean of 72° F. The solution aspirated was 4 per cent of evaporated sea salt in distilled water.

After testing, the specimens were cleaned of corrosion products by immersion for 1 to 3 days in 20-per-cent ammonium acetate solution containing 2 per cent free acetic acid, followed by gentle rubbing of the surface with the fingers or a soft brush as required; this solution at room temperature for the period stated does not produce a noticeable effect on any of the steels discussed here. This cleaning was followed by washing first in benzol and then in alcohol, and weighing. A notation was further made of the surface appearance after cleaning, the nature and location of pits, if any, etc.

MECHANICAL PROPERTIES

Steels of Group I.

The theoretical aspects of the iron-chromium carbon alloys have received considerable attention, leading to general agreement on several points in relation to the effect of chromium additions to carbon steels:

1. Elevation of the thermal critical range of the carbon steels.
2. Decrease in the carbon content of the eutectoid.
3. Marked lowering of the carbon change point by moderate rates of cooling.
4. Decrease in the rate of absorption of carbides in the solid solution and also of their re-precipitation, at heat-treatment temperatures.

Factors 1 and 4 account for the higher quenching temperatures required for the high-chromium steels as compared with carbon steels; 2 and 4 for the structural homogeneity of these steels over a wide range of tempering temperature, following suitable quenching; and 3 for the notable air-hardening properties of the alloys.

The original cutlery steels have been the subject of considerable discussion in the technical literature, resulting in a rather broad understanding of their properties. Recently, there has been some data presented on similar metals of a lower carbon content.

Practically nothing has appeared, however, concerning the variations of properties within the usual range of a chemical specification, nor has much mention been made of the higher-carbon chromium steels.

Early practice in the fabrication of the cutlery alloys employed quenching temperatures in the vicinity of 1650 to 1700° F. and the tensile and impact properties of steel A under these conditions are shown in Fig. 4. Two differences must be noted, in respect to these tests, from the methods of preparation and testing just described: the impact test bars were heat-treated after finish machining and the tension test bars, prior to testing, were ground on the gage length to 0.500 in. at the ends graduating down to 0.400 in. at the center along an arc of 12-in. radius. The form of the bars for this group of tests (and the few others conducted in the same manner) does not promote reliability in proportional limit determinations, but the results compare favorably with others considered later in this paper. It is admittedly difficult to determine with great accuracy the proportional limit of hardened steels due to the nature of the stress-strain curves, but the same operator was employed on all of the tests to be discussed and loads were increased by small increments, thus giving greater weight to the determinations. The outstanding features of these

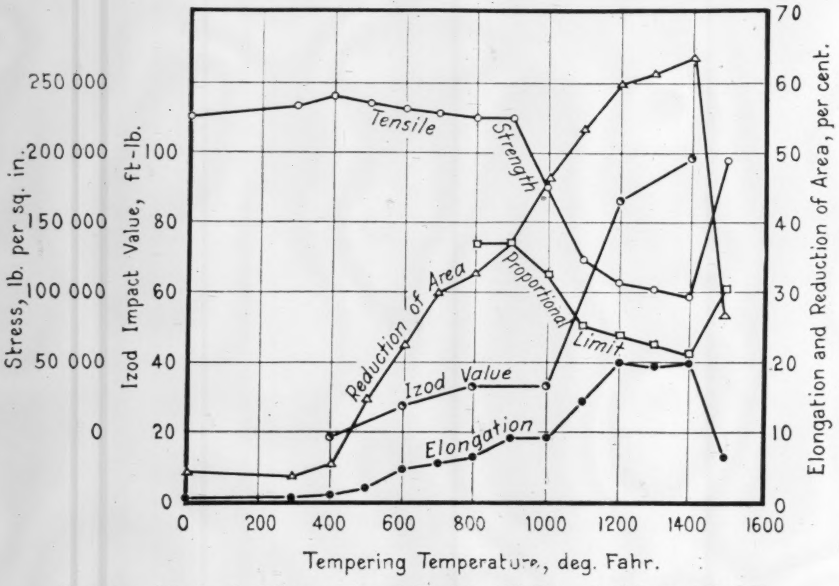


FIG. 4.—Mechanical Properties of Steel A, Oil Quenched from 1650° F.

few tests are the retention of the tensile strength of the hardened state until a temperature of 900° F. is reached, and the low ratio of proportional limit to tensile strength for all tempering temperatures

Following a recognition of the more desirable results obtainable, both in corrosion-resistance and mechanical properties, with the employment of higher quenching temperatures, the use of 1800 to 1900° F. for this purpose became the prevailing practice. The effect of increasing quenching temperature upon the tensile properties of steel A in the quenched condition is given in Table II. The tensile strength reaches a maximum at 1600 to 1650° F; brittleness at higher temperatures causes a rapid decrease in strength, but the hardness continues to increase throughout the range of these tests, with probably a maximum at 2000° F., the highest temperature used. These test bars also were prepared in the manner described for those of Fig. 4. The second part of the table illustrates the influence of the chromium content of these steels upon the mass effect in hardening. All of the bars were heat treated in the same furnace at the same time, the heat treatment being carried out on bars of the size indicated in the table; the time at the tempering temperatures was in this instance extended to two hours. The bars were machined to a uniform diameter throughout the gage length.

TABLE II.—MECHANICAL PROPERTIES OF STEEL A (CARBON 0.32 PER CENT. CHROMIUM 13.96 PER CENT).

Bar	Size as Treated, in.	Heat Treatment, deg. Fahr.[a]	Proportional Limit, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Brinell Hardness	Scleroscope Hardness
No. AC-1...	0.52	1300, Oil	.....	89 400	16.8	62.7	181	22
No. 4...	0.52	1400, Oil	.....	88 900	16.8	64.2	179	21
No. 10...	0.52	1500, Oil	.....	191 800	6.3	36.1	387	46
No. 9...	0.52	1550, Oil	.....	210 800	6.0	35.2	430	50
No. 8...	0.52	1600, Oil	.....	224 400	2.0	7.4	444	53
No. 12...	0.52	1650, Oil	.....	223 500	0.5	4.0	477	60
No. 17...	0.52	1700, Oil	.....	216 900	0.2	2.0	555	63
No. 5...	0.52	1800, Oil	.....	142 200	0	0.5	555	63
No. 6...	0.52	1900, Oil	.....	108 600	0	0	578	66
No. 11...	0.52	2000, Oil	.....	95 000	0	0	600	61
No. 33[b]..	3	1650, Oil; 1050, Air	86 950	145 660	12.0	40.1	332	42
No. 33[c]..	3	1650, Oil; 1050, Air	86 950	147 190	13.0	46.1	337	41
No. 34...	2	1650, Oil; 1050, Air	87 500	150 300	12.3	43.7	340	43
No. 35...	1	1650, Oil; 1050, Air	92 900	151 500	14.3	48.9	340	43
No. 36...	0.52	1650, Oil; 1050, Air	86 900	145 200	14.8	49.9	332	41

[a] All bars furnace cooled from 1550° F. prior to treatment.
[b] Surface.
[c] Center.

Oil quenching of steel C showed a maximum Brinell hardness of 555 on $\frac{3}{8}$-in. disks when cooling from 1900° F.; above this temperature slight softening occurred. Thus, contrary to the conditions obtaining in the use of the common alloy structural steels, an increase in the proportions of carbon and the alloying element lowers the maximum hardness obtainable with a given quenching medium.

Because of the previously noted slow carbide absorption in these steels, and the high temperatures required for accomplishing a given purpose when employing short heating periods, tests have been made of corrosion resistance and mechanical properties on samples quenched from 1700° F. up to 2100° F. and tempered between 600 and 1300° F. Tests of steel A had indicated that the brittleness observed in quenched specimens cooled from the higher temperatures was only partly removed by reheating to 400° F., but almost completely disposed of on tempering at 600° F., at least in so far as the develop-

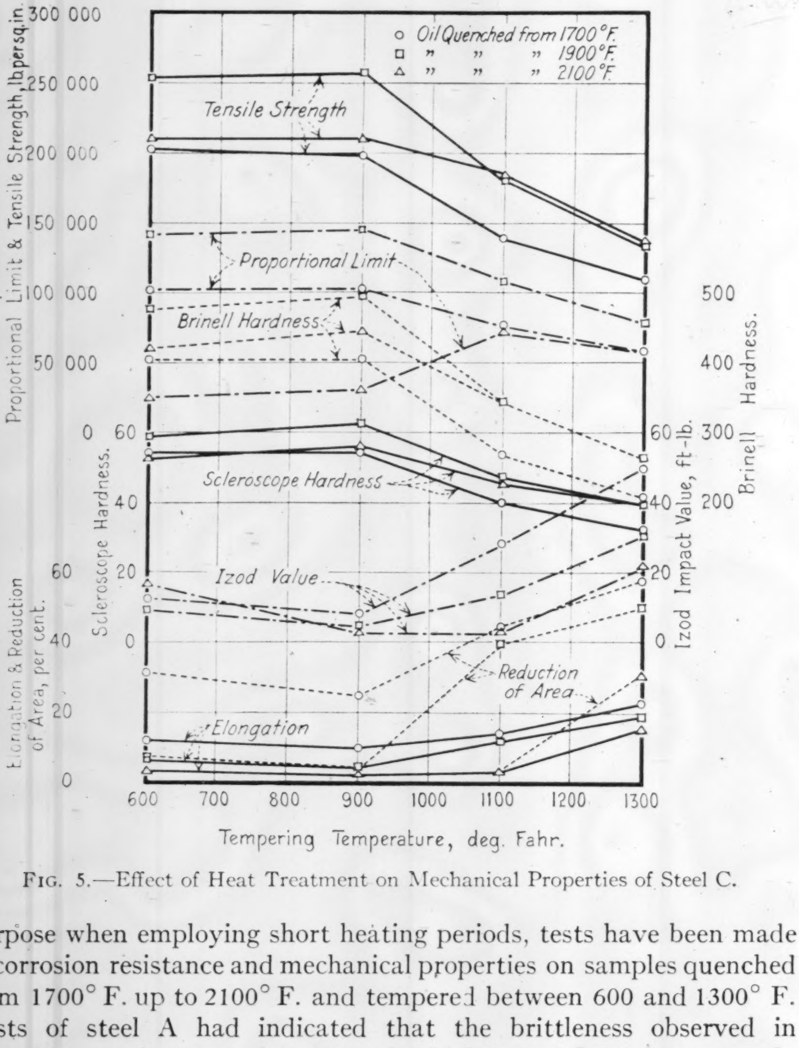


FIG. 5.—Effect of Heat Treatment on Mechanical Properties of Steel C.

ment of maximum static tensile properties was concerned. Most of the useful quenching and tempering temperature combinations are therefore included within these limits.

The results obtained on steel C are reproduced graphically in Fig. 5. The best combination of properties is secured with the 1900° F. quench; lower (and frequently higher) quenching temperatures produce lower values of both proportional limit and tensile strength.

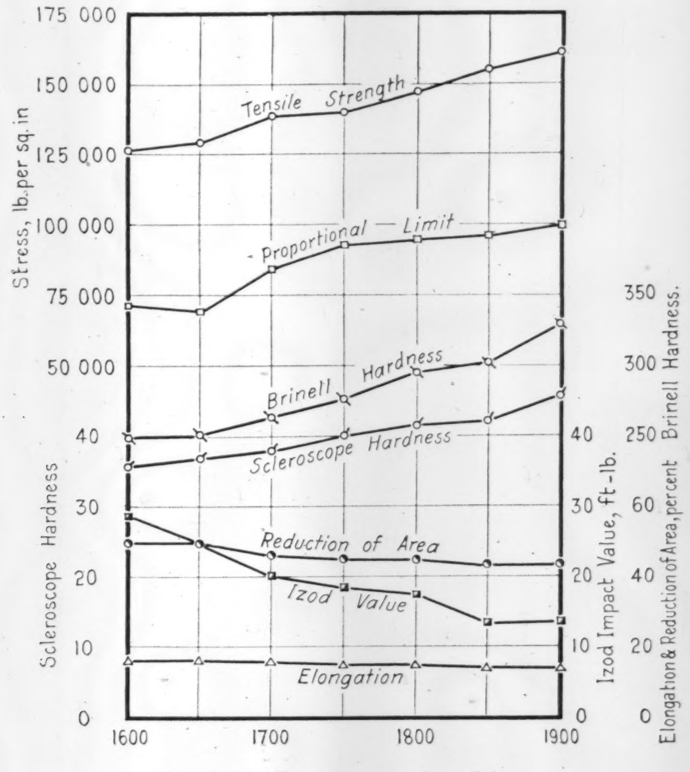


FIG. 6.—Effect of Oil-Quenching Temperature on Mechanical Properties of Steel C.

Comparison of Fig. 5 with Fig. 4 indicates that composition may have a marked effect upon the development of high strength and hardness when using low quenching temperatures. Steel C also shows slight indications of secondary hardening between 600 and 900° F. following rapid cooling from 2100° F.

Fig. 6 (heat treatments performed on 1-in. round bars, all tempered at 1100° F.) shows the very gradual change of properties of steel C with increased quenching temperature. The only sharp break in the curves is in that of the proportional limit between 1650 and 1750° F. This value and tensile strength are greatly increased without much loss of ductility, as measured by the elongation and reduction of area. The impact strength, however, decreases rapidly. A very interesting feature is the gradual hardness increase, which is, perhaps, better shown by the figures of Table III. This slow gradation is of distinct advantage in the local hardening of structural parts, largely avoiding, as it does, that sharp hardness gradient at the end of the hardened zone (and co-existing stress localization) which such practice develops in carbon and most alloy steels.

A few tension and impact tests were made on steel D under the same conditions as have been described for the tests of Fig. 4, and are recorded in Table IV. Because of the method of testing, no attempt should be made to compare the ductility (as measured by elongation and reduction of area) of these specimens with other values obtained on bars of uniform cross-section in the gage length. But it is apparent that proportional limit and tensile strength equal to those of the lower carbon steels are obtainable with this analysis; hardness values are reported here equal to those obtained with steel C under the best conditions and it is possible that modification of the quenching temperature would yield values equal to those of steel A.

TABLE III.—HARDNESS TESTS OF STEEL C.

Obtained on disks $\frac{3}{8}$ in. thick, 1 in. in diameter, quenched in oil from the temperatures noted.

Quenching Temperature, deg. Fahr.	Brinell Hardness	Scleroscope Hardness	Quenching Temperature, deg. Fahr.	Brinell Hardness	Scleroscope Hardness
1400	170	26	1625	387	45
1500	170	26	1650	402	47
1525	252	30	1675	444	50
1550	286	35	1700	512	61
1575	351	40	1800	512	61
1600	364	43	1900	555	63

Tension tests have not been made on steels E and F but from the hardness data recorded in Fig. 7, as obtained on disks $\frac{3}{8}$ in. thick and 1 in. in diameter, some conception of their properties is obtainable. Steel E develops maximum hardness at 1800° F. but the same effect is not obtained for steel F until 2000° F. is reached; for the latter steel, hardness changes are slower at both lower and upper ends of the "hardening range." These effects may be due in part to the vanadium content of steel F but it is most probable that silicon is the dominant factor. On tempering, steel F retains its hardness at slightly higher temperatures than does steel E, then decreasing at about the same rate but finally more slowly as the thermal critical range is approached.

With its 7 per cent of chromium and 7.5 per cent of tungsten, steel G stands out as markedly different from the other steels studied, approaching in composition the self-hardening and the high-speed steels. Its properties, as modified by various heat treatments and recorded in Fig. 8, somewhat resemble those of modern high-speed

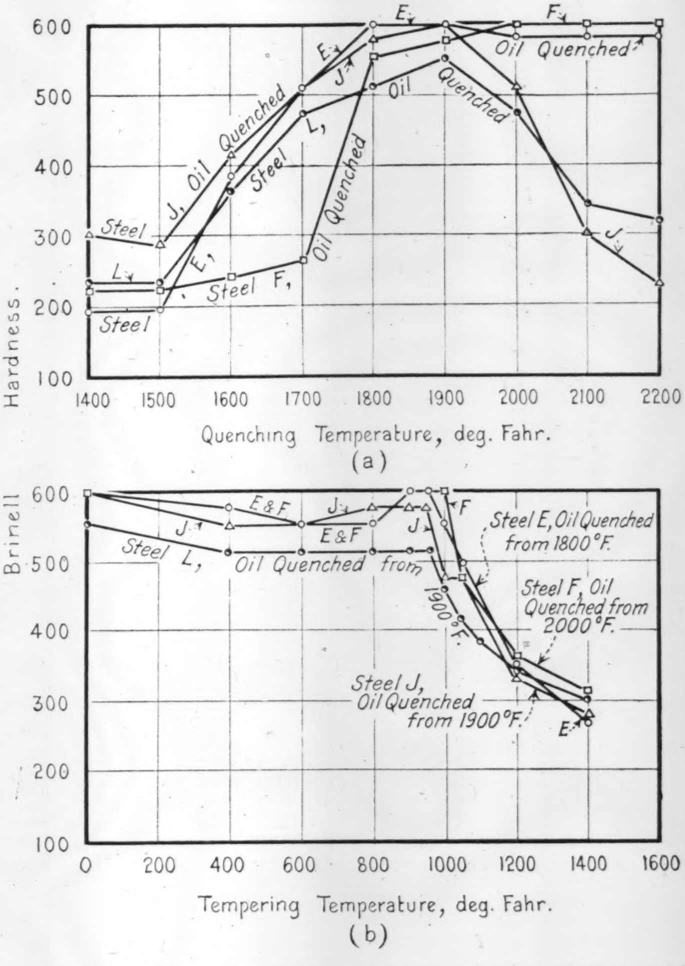


FIG. 7.—Effect of Heat Treatment on Hardness of Steels E, F, J and L:
(*a*) Variation of hardness with quenching temperature.
(*b*) Variation of hardness with tempering temperature.

steel. When oil quenched from 1700° F., the resultant mechanical properties vary with tempering temperature in a manner similar to those of the simple chromium steels just described. Increasing the quenching temperature to 1900° F. causes the tensile properties of the hardened state to persist with tempering temperatures as high as 1100° F.; along with high hardness in the tempering range of 600 to 1100° F., a reasonable resistance to impact is maintained. When the hardening temperature is increased to 2100° F., progressive rehardening occurs on tempering with a maximum in the vicinity of 1100° F. The hardness under these conditions is greater than was observed following any heat treatments applied to any of the steels tested. When utilizing this steel in the "toughened" state, the

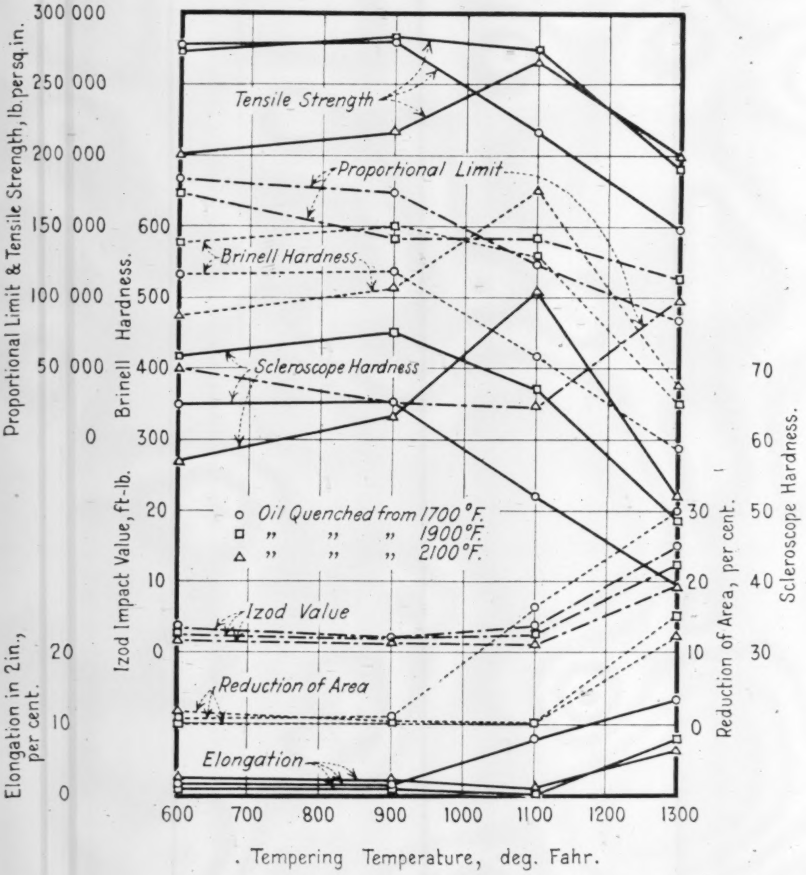


FIG. 8.—Effect of Heat Treatment on Mechanical Properties of Steel G.

high quenching temperatures will be noted to offer no advantages in respect to strength and ductility.

Steel H, with 17 per cent of chromium and moderately high carbon does not develop in the tempered condition a hardness value much above 500 Brinell on oil quenching from up to 1900° F. The increased carbon is apparently counterbalanced in its hardening effect by the high chromium content and probably to some degree also by the added silicon. When using low quenching temperatures, the proportional limit drops rather uniformly with increase in tempering temperature, in contrast to the uniformity in the tensile strength up to 900° F. On raising the quenching temperature to 1900° F., the

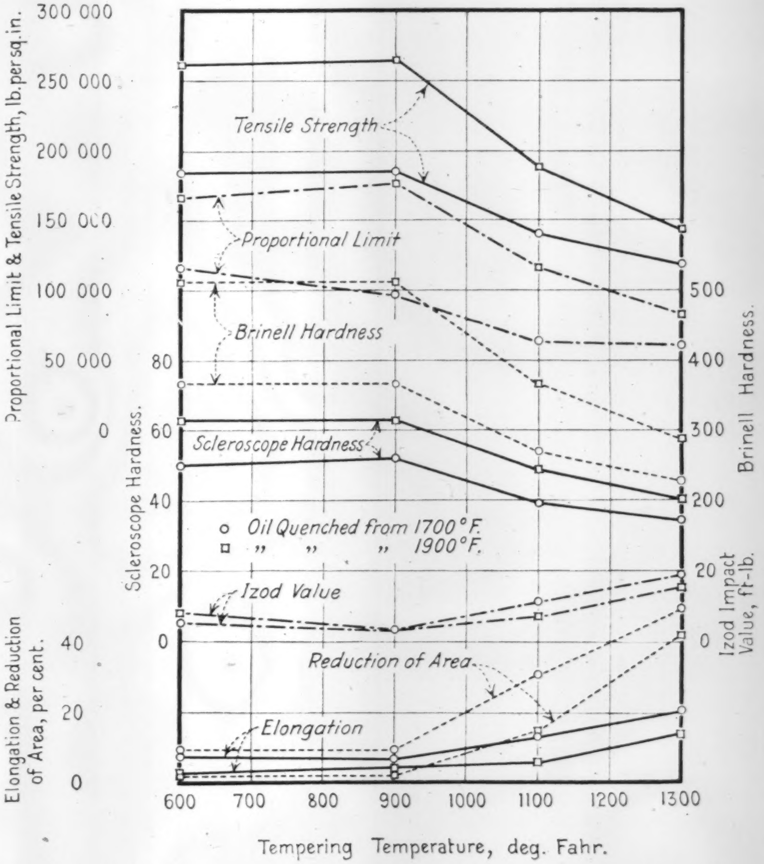


FIG. 9.—Effect of Heat Treatment on Mechanical Properties of Steel H.

proportional limit is greatly increased and almost parallels the tensile strength within the tempering range of 600 to 900° F.

No impact tests were made on steel I. The original bar was $\frac{5}{8}$ in. in diameter and on this account the tension test bars were 0.38 in. in diameter in the gage length at the time of heat treatment, being subsequently ground to 0.35 in. for testing. The ends were equipped with $\frac{5}{8}$-in. standard threads. Extensometer readings were taken over a parallel length of 2 in., but elongations were measured on a length equal to four times the diameter. The characteristics displayed by this steel are not essentially different from those of the chromium steels previously described. Reduction of the temperature intervals between successive tempering operations permits the observation that increase in the quenching temperature from 1700° F. to 1900° F. causes the retention of maximum tensile strength and hard-

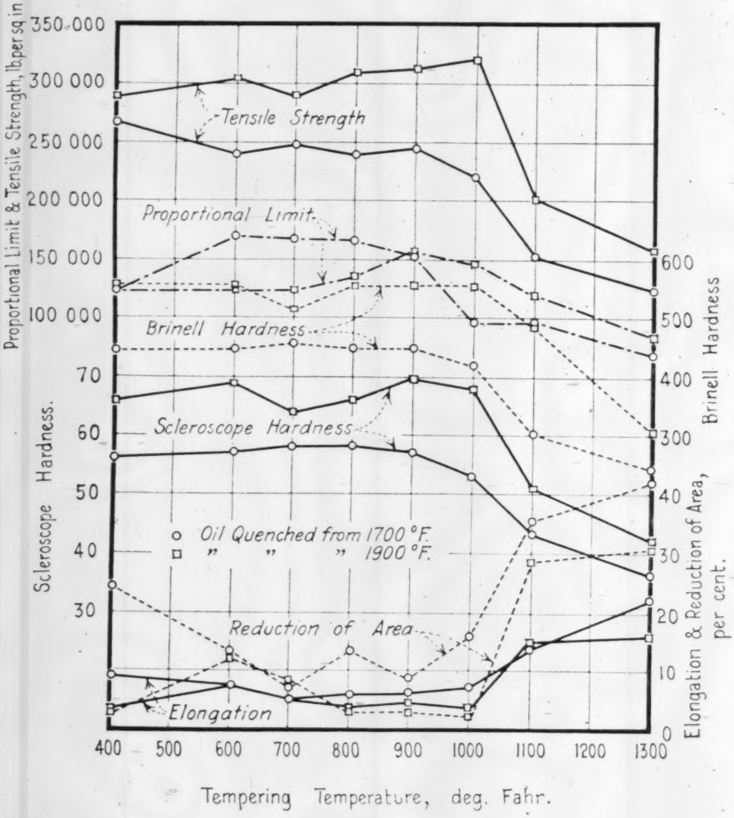


FIG. 10.—Effect of Heat Treatment on Mechanical Properties of Steel I.

ness at slightly higher tempering temperatures. The increase with this temperature (between 700 and 900° F.) of the proportional limit of bars cooled in oil from 1900° F. is noteworthy.

Tests of steel J, made under the conditions outlined in the discussion of Fig. 4, are recorded in Table IV; hardness tests on disks similar to those of steels E and F are shown graphically in Fig. 7. Comparing steels I and J, the 1700° F. quenching produces greater hardness in the latter material, due probably to both the increased carbide-dissolving power of the higher-chromium metal and also the restraining effect of silicon on hardness development. Quenching from 1900° F. produces practically equal hardness, the lower chromium of steel I tending toward higher hardness and its silicon content in the

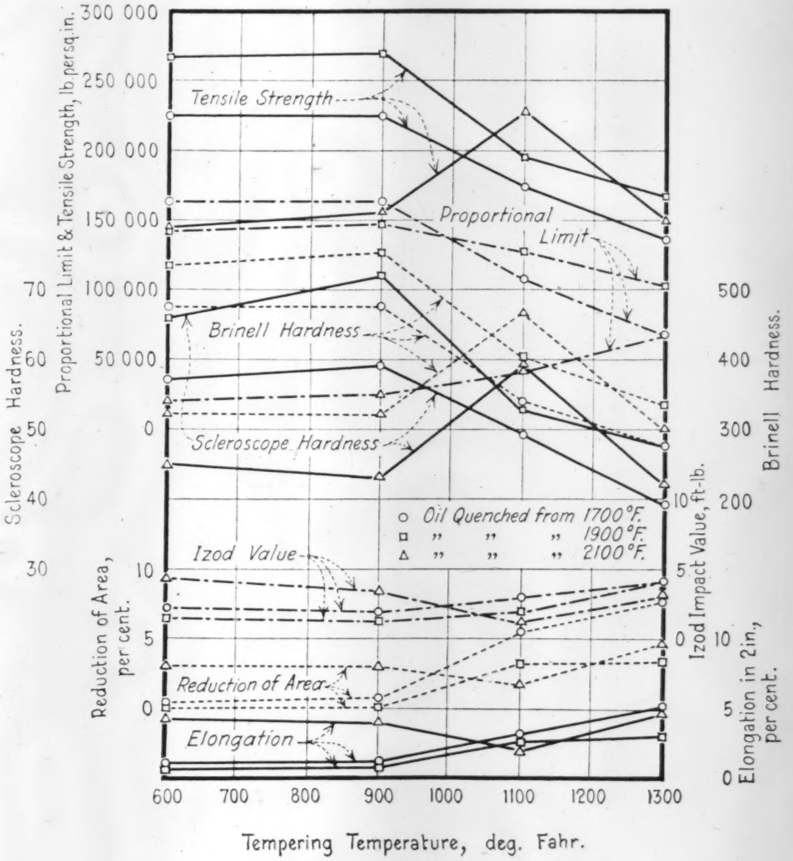


FIG. 11.—Effect of Heat Treatment on Mechanical Properties of Steel K.

TABLE IV.—MECHANICAL PROPERTIES OF STEELS D, J, M, M1 AND M2.

Bar	Heat Treatment, deg. Fahr.	Proportional Limit, lb. per sq. in.	Tensile Strength lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Value, ft-lb.		Brinell Hardness	Scleroscope Hardness
						A	B		
STEEL D (CARBON 0.53 PER CENT, CHROMIUM 13.36 PER CENT)[a]									
No. AC-406	As annealed	56 100	106 700	22.9	41.0	38	44	212	26
No. 400	1700, Oil; 400, Air	......	202 400	0.3	0.5	..	..	555	60
No. 401	1700, Oil; 600, Air	......	234 000	0.3	2.5	...	..	512	56
No. 402	1700, Oil; 800, Air	148 600	251 800	1.0	2.8	..	..	555	68
No. 403	1700, Oil; 1000, Air	127 600	207 600	3.0	17.6	6.5	8	477	57
No. 404	1700, Oil; 1200, Air	71 300	124 500	19.0	45.2	21.	31.5	269	33
No. 405	1700, Oil; 1400, Air	61 100	107 200	25.8	52.7	50	50	235	29
STEEL J (CARBON 0.80 PER CENT, CHROMIUM 18.16 PER CENT)[a]									
No. AC-317	As annealed	40 700	95 700	27.8	55.4	18	15.5	207	..
No. 300	1700, Oil; 400, Air	......	215 900	0.3	0.5	4	4	512	54
No. 301	1700, Oil; 600, Air	......	218 100	0.3	0.5	5	7	512	56
No. 302	1700, Oil; 800, Air	143 100	254 400	1.8	2.0	5	4.5	512	60
No. 303	1700, Oil; 1000, Air	122 700	233 100	2.3	10.1		..	477	55
No. 304	1700, Oil; 1200, Air	71 600	137 800	12.0	27.7	15.5	17	302	37
No. 305	1700, Oil; 1400, Air	66 200	115 100	18.8	40.0	21	19.5	241	29
STEEL M (CARBON 0.09 PER CENT, CHROMIUM 15.96 PER CENT)									
No. X- 50	As received	40 700	84 030	29.0	71.5	97	..	160	26
No. X- 51	1650, Furnace Cooled	32 600	75 120	34.0	70.8	90	..	146	24
No. AC-950[b]	1800, Furnace Cooled	30 600	86 400	25.3	57.1	..		...	
No. 951[b]	2000, Furnace Cooled	27 500	77 400	26.8	55.9	40	40.5	137	22
No. X- 52	1800, Water Quenched	30 600	169 090	4.3	5.1	..	..	324	41
No. AC-952[b]	2000, Water Quenched	28 100	155 400	2.0	2.4	7	7	286	40
STEEL M1 (CARBON 0.09 PER CENT, CHROMIUM 15.26 PER CENT)									
No. X-104	As received	34 600	71 900	34.3	73.8	..	..	149	..
No. AC-987[b]	1800, Water Quenched	10 200	135 500	7.5	10.1	8	7.5	255	36
No. 988[b]	2000, Water Quenched	none	131 100	4.0	5.1	..	..	...	..
No. 985	1800, Water; 1000, Air	33 200	123 800	22.0	57.5	23	21	235	34
No. 986	1800, Water; 1000, Air	35 700	123 800	22.0	58.3	27	20	241	35
No. 983	2000, Water; 1000, Air	33 200	122 200	21.5	52.4	8.5	9	235	33
No. 984	2000, Water; 1000, Air	35 700	122 500	21.3	54.8	6	6	235	34
STEEL M2 (CARBON 0.11 PER CENT. CHROMIUM 12.16 PER CENT)									
No. AC-979[c]	1800, Water Quenched	84 000	184 000	2.0	....	4.6	3.1	418	..
No. 981[c]	2000, Water Quenched	84 300	188 400	1.5	....	4.6	3.9	418	..
No. 980[c]	1800, Water; 1000, Air	83 700	164 000	1.8	....	4.6	5.2	387	..
No. 982[c]	2000, Water; 1000, Air	82 300	166 250	1.5	....	6.3	7.0	387	..

[a] All bars furnace cooled from 1600° F. prior to heat treatment.

[b] Forged to $\frac{7}{8}$ in. diameter prior to heat treatment.

[c] Izod values computed by direct proportion from bar 0.25 in. thick to standard 0.394-in. thickness.

opposite direction. An interesting feature of the tests of steel J is the interruption in hardness decrease on tempering disks quenched from 1900° F. at between 1000 and 1050° F., presumably related to the variation in rates of decomposition of austenite and martensite.

TABLE V.—MECHANICAL PROPERTIES OF STEELS P, Q AND R.

Bar	Heat Treatment, deg. Fahr.	Proportional Limit, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Value, ft-lb.		Brinell Hardness	Scleroscope Hardness
						A	B		
STEEL P (CARBON 0.18 PER CENT, SILICON 0.98 PER CENT, CHROMIUM 15.84 PER CENT)									
No. AC-832	As received	38 200	78 700	32.8	60.6	1.5	2.5	156	23
No. 833	1600, Furnace Cooled	40 700	77 100	34.3	70.4	2	2.5	156	23
No. 835	1800, Furnace Cooled	35 800	72 300	38.0	69.6	2	2	149	23
No. 837	2000, Furnace Cooled	35 700	72 600	33.0	55.9	1	1	149	22
No. 839	2200, Furnace Cooled	33 200	72 100	26.7	54.2	1	1	149	23
No. 834	1600, Water Quenched	28 000	74 800	35.0	66.6	3.5	4.5	149	23
No. 836	1800, Water Quenched	20 500	91 500	6.0	7.9	2	2	166	25
No. 838	2000, Water Quenched	25 700	144 700	2.5[a]	2.8	2	2	302	41
No. 840	2200, Water Quenched	30 600	129 400	2.3[a]	2.8	1.5	1.5	269	36
No. 841	1800, Water; 1000. Air	28 100	111 800	17.1	38.6	1.5	1.5	163	24
No. 842	2000, Water; 1000, Air	38 200	156 000	12.0	17.6	3	3	293	41
STEEL Q (CARBON 0.64 PER CENT, CHROMIUM 27.21 PER CENT)									
No. 892	As received	30 500	95 700	21.0	37.0	1.5	2	183	26
No. 893	1600, Furnace Cooled	48 400	96 400	15.8	30.1	1	1	187	25
No. 895	1800, Furnace Cooled	50 900	98 300	18.0	34.1	1	1	187	26
No. 897	2000, Furnace Cooled	50 900	92 200	12.9	28.9	1	1	187	28
No. 899	2200, Furnace Cooled	50 900	89 300	12.9	24.3	1	1	192	27
No. 894	1600, Water Quenched	45 000	88 600	21.8	34.4	1	1	179	26
No. 896	1800, Water Quenched	46 000	93 800	19.2	36.5	1	1	187	26
No. 898	2000, Water Quenched	43 300	112 400	10.8	14.8	1	1	217	31
No. 900	2200, Water Quenched	43 300	110 000	9.8	9.0	1.5	1	241	33
No. 901	1800, Water; 1000, Air	45 800	98 000	13.3	19.7	1	1	196	31
No. 902	2000, Water; 1000, Air	41 100	114 400	5.8	17.8	1	1	223	32
STEEL R (CARBON 0.24 PER CENT, CHROMIUM 20.44 PER CENT, COPPER 1.08 PER CENT)									
No. AC-600	As received	25 700	112 800	20.0	35.0	4	4	207	32
No. 601	1600, Furnace Cooled	45 400	85 300	32.0	62.3	1	2	170	26
No. 603	1800, Furnace Cooled	44 800	82 000	30.2	59.3	2	2	163	26
No. 605	2000, Furnace Cooled	41 400	80 200	28.5	59.5	1	1	163	27
No. 516[b]	2000, Furnace Cooled	46 000	80 800	22.5	52.3	1	1		
No. 607	2200, Furnace Cooled	38 200	80 100	6.8[a]	7.4	1	1	170	27
No. 602	1600. Water Quenched	30 600	86 000	30.0	60.8	6	15	163	24
No. 604	1800. Water Quenched	25 400	110 500	20.2	37.6	4	5	203	27
No. 606	2000, Water Quenched	25 400	120 900	19.2	31.4	25	23	187	23
No. 515[b]	2000, Water Quenched	23 600	107 500	13.0[a]	10.7	33	33	...	
No. 608	2200, Water Quenched	25 400	102 000	29.7	26.0	31	27	174	25
No. 517[b]	1800. Water; 1000, Air	66 700	123 500	2.8[a]	2.8	1.5	1.5	228	35
No. 518[b]	2000. Water; 1000. Air	36 500	127 600	10.3[a]	9.1	5.5	14	207	30

[a] Broke in fillet.
[b] Test bars heat treated after finish machining

The mechanical properties of steel K are reproduced in Fig. 11. The proportional limit on bars quenched from 1700° F. decreases rapidly as the tempering temperature rises above 900° F.; higher quenching temperature (1900° F.) produces a lower proportional limit but greater stability over the tempering range of 600 to 1300° F. There is also a sharp rehardening when quenching from 2100° F. as in the chromium-tungsten steel; similarly, for these conditions of thermal treatment, the proportional limits are extremely low. Hardness data on disks $\frac{3}{8}$ in. thick and 1 in. in diameter of steel L are included in Fig. 7. A comparison of the hardness of steels K and L for like heat treatments indicates that the essential difference of 4 per cent of chromium produces a decidedly lower hardness in the steel with the greater proportion of this element. It is also of interest to note from Fig. 7 that variations of 0.6 per cent of carbon, 1.0 per cent of silicon and 14.0 per cent of chromium, in these higher-carbon chromium steels, do not markedly affect the rate of hardness increase as the quenching temperature rises; 3 per cent of silicon, however, has a pronounced influence.

Rigid conclusions from these few tests are not possible but the indications are that within the range of compositions studied (excluding the chromium-tungsten steel) the maximum tensile strength obtainable by heat treatment does not vary widely. Likewise the maximum hardness is confined to a narrow range. But, for high-chromium steel of a given carbon content, small increases in the percentage of chromium may decrease the maximum hardness obtainable by heat treatment. High quenching temperatures such as are commonly used to obtain maximum hardness (*i. e.* about 1900° F.) may not be successful because of the retention of much austenite on rapid cooling, and decrease of the temperature may likewise fail of accomplishment due to insufficient absorption of carbides prior to quenching. The effect is less noticeable in the highest carbon steels studied. Silicon has a marked effect upon the hardening of these steels, increasing the temperature required for maximum hardness development and decreasing the hardness obtainable. There is reason to believe that the effect of silicon is less in the higher carbon steels. Rehardening on tempering, following the use of the usual quenching temperatures is slight.

Heat treatment of these "hardenable" steels is thus closely related to several factors:

1. The percentages of carbon and chromium in the steel.
2. The degree of absorption of carbides as controlled by factor 1, temperature and time.

3. The amount of austenite retained on quenching as controlled by factors 1 and 2.
4. The decomposition of austenite and martensite on tempering as controlled by factor 1, temperature and time.

It is suggested that these natural limitations imposed in the heat treatment of the high-chromium alloys may be of value when considering specification limits for steels to meet high hardness requirements.

Steels of Group II.

A few tests have been made of steels of the "stainless iron" type and are recorded in Table IV. Great changes in the hardness and the tensile strength of these steels may be effected by heat treatment in spite of their very low carbon content. But the degree of this hardness increase is closely related to the chromium content of the steel, as is also the proportional limit. The latter value is extremely low for steels with over 15 per cent of chromium, particularly in relation to the tensile strength; it varies greatly with heat treatment and in one test was not found at all, the stress-strain diagram being distinctly curved above the starting point of 2500 lb. per sq. in. It should be noted here that steel M2 was in the form of $\frac{1}{4}$-in. sheet, the tension test bars being 1 by $\frac{1}{4}$ in. in cross-section over the gage length of 2 in. With such hard steels, in this form, it is possible that maximum tensile strength and elongation were not developed in testing. The significant fact, however, is the greatly increased proportional limit, resulting from the decrease in chromium content; the effect can hardly be ascribed to the 0.02 per cent higher carbon.

Sufficient material for tension tests of steel N was not available. It may be predicted with some certainty that similar heat treatments will produce in this steel increased tensile strength and greatly increased proportional limit over those obtainable from steel P, and the same effect but in a lesser degree in comparison with steel O. Tension tests of steel O are also not available but it was found possible with quenching temperatures of 1750 to 2000° F. to reach a Brinell hardness value of slightly over 400 on thin sections.

This latter hardness contrasts strongly with the maximum value of 302 obtained on 1-in. round bars of steel P and points to the interference with the hardening of these low-carbon chromium steels exerted by the element silicon. The high quenching temperature required for effective hardening is traceable to the same cause. None of the heat treatments applied to this steel produced a very great effect upon the proportional limit although causing considerable variation in the tensile strength. This is believed to be due primarily to the influence of the high chromium percentage. The extremely low resistance to impact in notched bars of this metal, regardless of the heat treatment, is in striking contrast to the results obtained on steels M and M2 and has not been traced to any cause other than the silicon content.

Only very slight hardening is possible with steel Q; the increase of hardness by quenching is probably due, in part at least, to a greater percentage of carbon retained in solid solution. Annealing causes an appreciable increase in proportional limit over that of the "as received" condition; this value is unaffected by short exposures at relatively high temperatures (up to 2200° F.) followed by very slow cooling. On quenching from temperatures between 1600 and 2200° F., the proportional limit is lower than after slow cooling and changes but little over the above quenching temperature range. Hardness and tensile strength are increased by quenching from 2000° F. or above, at the expense of ductility; as with other chromium steels, the properties of the quenched state are retained after tempering at 900 to 1000° F. Resistance to impact is extremely low, regardless of heat treatment.

Steel R, an iron-carbon-chromium alloy containing copper, possesses unusual properties. As received from the manufacturer, it exhibited good ductility and tensile strength, a low proportional limit and rather low resistance in the Izod impact test. Slow cooling following short heating periods within the range used decreases the hardness and tensile strength, destroys the resistance to impact and, as in the case of the very high-chromium steel Q, causes a marked increase in proportional limit which is lowered slightly by increase in the annealing temperature. Contrary to the behavior of Steel Q, however, there occurs a very great increase in ductility as measured by the elongation and reduction of area. Quenching from 1800° F. reproduces the properties of the original material. Increasing the quenching temperature beyond this makes possible an increase in impact resistance to from six to eight times the value obtained from the original metal, without appreciably affecting the tensile properties. For many applications the importance of this fact cannot be overlooked for, despite many desirable qualities, the very high-chromium, low- and medium-carbon steels are decidedly "brittle" in notched bar impact. As with other chromium steels, the proportional limit after high-temperature quenching is extremely low. An interesting feature is the lack of uniformity in the ratio of tensile strength to Brinell hardness. Desirable properties are developed in steel R, following tempering of quenched specimens, chiefly in respect to an increase in the proportional limit, but the good impact properties are at the same time impaired.

No material of similar composition but without copper was available to determine whether the effects noted in this steel were largely due to the copper content, although this does not seem likely. The presence of higher carbon and higher chromium without copper (steel Q) yielded a somewhat similar, yet quite different product. Steel S, with nearly the same carbon and chromium proportions, but containing silicon and tungsten additions, failed to develop high impact resistance by high-temperature heat treatment. In fact, without appreciable change in hardness, such thermal treatment destroys the normally good tensile properties; rapid cooling from 2200° F. so embrittles the metal as to prevent the possibility of light machining, or even stenciling, without breakage.

Steels of Group III.

The high-nickel steels, with 25 per cent or more of nickel, have been examined from time to time and found to contain carbon percentages ranging from 0.15 to as high as 0.90. The tensile properties are largely affected by the amount of low-temperature forging or cold working, and subsequent heat treatment. With annealing temperatures that have been employed in practice (up to 1600° F.) the effect of working is very largely removed and the rate of cooling following heat treatment has little, if any, effect on tensile properties. Within the range of 25 to 35 per cent nickel, these properties seem to be controlled more by the carbon than by the nickel content. In the annealed state, the metal is very soft and tough, values for proportional limit having been as low as 15,000 lb. per sq. in. with a tensile strength of 75,000 lb. per sq. in. and an elongation of 60 per cent. Manganese has been added to these alloys up to 2 per cent to increase the ease of working in heavy sections. Addition of chromium raises both the proportional limit and tensile strength and reduces the ductility slightly.

The presence of large amounts of chromium in these nickel steels appears to make them even more susceptible to the influence of working at moderate temperatures. From the same source, materials similar to steels X and Y have been obtained at different times in which the proportional limit varied between 20,000 and 80,000 lb. per sq. in. while the tensile strength varied only from 105,000 to 135,000 lb. per sq. in.; the minimum elongation was 20 per cent. These steels, when cold worked, are affected to a lesser degree by heat treatment than the simple high-nickel steels. Steels with moderately high proportional limit (steel X) do not have their properties changed to a great degree (as do the plain nickel steels) by heating as high as 1600° F., although this value does fall off slowly as

TABLE VI.—MECHANICAL PROPERTIES OF STEELS S, Y, X AND Z.

Bar	Heat Treatment, deg. Fahr.	Proportional Limit, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Value, ft-lb.		Brinell Hardness	Scleroscope Hardness
						A	B		
STEEL S (CARBON 0.32 PER CENT, SILICON 2.77 PER CENT, CHROMIUM 19.29 PER CENT, TUNGSTEN 2.54 PER CENT)									
No. AC-880	As received..........	66 500	115 900	13.0	35.5	1	1	235	34
No. 882	2000, Furnace Cooled	63 600	93 400	3.3	4.0	1	1	217	33
No. 883	2200, Furnace Cooled	58 570	86 330	1.0	1.2	1.5	1.5	217	35
No. 881	2000, Water Quenched	58 800	96 600	6.0	6.7	1	1	217	33
No. 884	2200, Water Quenched	[a]	[a]	[a]	[a]	2	[a]	217	33
STEEL Y (CARBON 0.39 PER CENT, SILICON 1.07 PER CENT, NICKEL 20.91 PER CENT, CHROMIUM 7.57 PER CENT)[b]									
No. AC-206	As received..........	48 300	107 600	44.3	60.1	90	90	196	26
No. 207-A[c]	As received..........	47 400	104 700	39.0	48.0	..	..	196	24
No. 207-B[d]	As received..........	42 500	106 600	36.5	45.2	94	92	207	25
No. 200	1500,[e] Furnace Cooled	49 900	108 200	33.3	53.3	..	..	207	25
No. 201	1800,[e] Furnace Cooled	35 600	95 400	44.3	60.1	89	92	168	20
No. 209	2200, Furnace Cooled	.....	.....	....	....	68	67	156	25
No. 202	1600, Water Quenched	37 100	105 200	33.8	57.2	..	..	205	26
No. 203	1800, Water Quenched	37 600	103 800	45.5	64.4	..	..	187	23
No. 204	2000, Water Quenched	37 600	96 000	54.5	61.8	..	..	179	23
No. 205	2200, Water Quenched	38 100	94 300	51.5	69.1	93	94	163	24
No. 977[f]	2200, Water Quenched	33 400	100 700	53.5	69.9	90	94	156	22
No. 978[g]	2200, Water; 1300, Air	35 800	104 300	45.7	60.9	92	92	156	24
STEEL X (CARBON 0.46 PER CENT, SILICON 1.67 PER CENT, NICKEL 22.70 PER CENT, CHROMIUM 7.31 PER CENT)									
No. X-101[h]	As received..........	57 900	110 700	28.0	47.3	..	..	...	..
No. 102[h]	1200, Water Quenched	54 200	109 900	29.8	45.6	..	..	...	..
No. 103[h]	1600, Water Quenched	51 900	111 200	27.0	41.3	..	..	...	..
No. AC-956	1900, Water Quenched	35 650	106 440	42.3	62.3	93.5	95.5	174	28
No. 957	2200, Water Quenched	30 550	95 500	56.0	70.8	88	90	149	24
No 975	2200, Water Quenched	30 500	92 200	53.5	70.7	94	92	156	24
No. 976[g]	2200, Water; 1300, Air	41 070	107 560	42.5	49.8	94	91	170	26
STEEL Z (CARBON 0.35 PER CENT, SILICON 2.45 PER CENT, NICKEL 25.80 PER CENT, CHROMIUM 16.85 PER CENT)									
No. AC-953	As received..........	38 200	109 200	25.0	39.5	..	.	...	..
No. 954	2200, Water Quenched	28 200	95 500	25.8	23.6	91	91	163	27
No. 955[i]	2200 Water, 1300 Air	50 930	130 120	21.8	31.1	39.5	34.5	235	33

[a] Broke tensile bar transversely four times during light turning. Izod bar broke longitudinally at one end in stenciling.

[b] All bars, except those "as received," furnace cooled from 1550° F. prior to heat treatment.

[c] Center of 3-in. diameter bar.

[d] Edge of 3-in. diameter bar.

[e] Held at temperature 7 hours.

[f] 3-in. round forged to 1-in. round prior to heat treatment.

[g] Held at tempering temperature for 2 hours.

[h] Tests cut from center of 2-in. diameter bar.

a result of increasing temperature within this range. Water quenching following heating to between 1600 and 2200° F. reduces the proportional limit to between 25,000 and 40,000 lb. per sq. in. and above 1800° F. causes a reduction of the tensile strength; slow cooling following long periods of heating at 1800° F. has a similar effect. For those steels containing about 7 per cent chromium, none of the heat treatments used greatly modify the impact value, although the Brinell hardness varies rather widely.

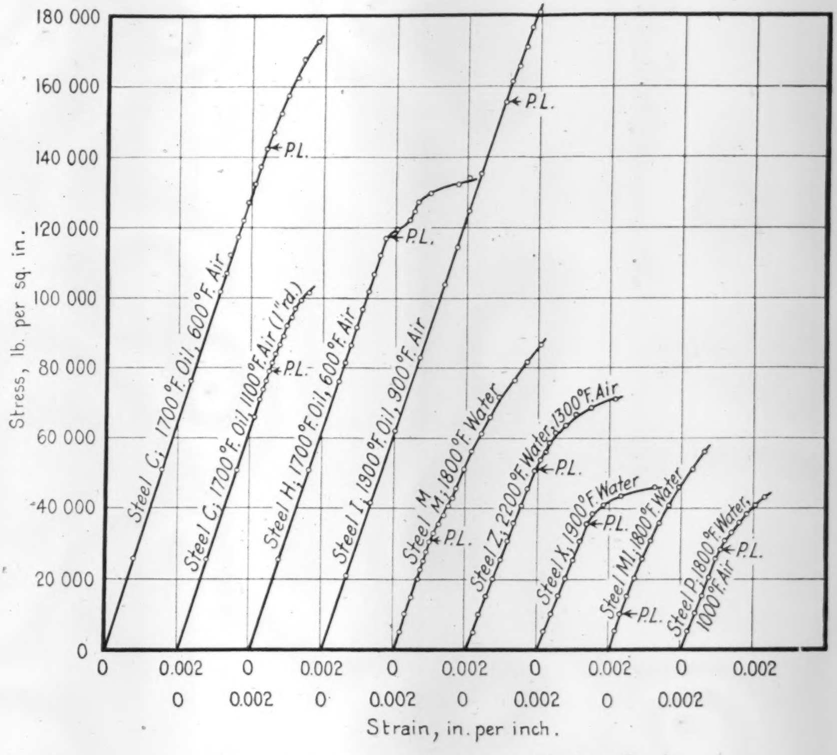


FIG. 12.—Stress-Strain Diagrams for Various Steels.

Increasing the chromium content to 17 per cent undoubtedly increases the ease of work-hardening but in the softened state "as received," or after high-temperature quenching, the properties are not markedly different from those of the lower-chromium nickel steels with the exception of inferior ductility in the tension test. Reheating at 1300° F. after high-temperature quenching, however, causes in steel Z some structural change that is accompanied by a very marked increase in proportional limit, tensile strength and hardness; the impact strength drops to an exceptionally low figure for metals of this class. A similar though less marked change results in steel X from the same treatment, unaccompanied by the loss of impact resistance. In steel Y, practically no modification of properties has been produced by this thermal treatment.

Mention has previously been made of the difficulty of determining the proportional limit in the hardened chromium steels. In some of the steels of groups 2 and 3, it is equally difficult because of the very slow change of curvature of the load-extension curve after the proportional limit has been passed. A few typical curves are given in Fig. 12.

CORROSION TESTS

The destruction of metal products by corrosion has for centuries driven man toward the preservation of these materials by various protecting coverings and also to the search for substitutes for, or improvements in, the metals used that would insure against loss, or at least markedly reduce it. In these efforts, estimation of success was at first obtained through the behavior of finished articles actually exposed to the influences that they were intended to withstand; but such methods of study, by reason of the time involved, could not keep pace with rapid metallurgical developments and the accelerated corrosion test came into being—a laboratory study to effectively replace the years of observation of the older method. How well it has performed the function for which it was originally intended cannot be discussed here—undoubtedly in some cases it has served its purpose and in others it has failed miserably. Its success must depend upon an understanding of the fundamentals of the problems involved, so that any means of intensification of working conditions that is adopted will affect all metals tested in the same relative degree. Even then, a correlation of the results of the accelerated test with service must be available to prove its value.

Recent extensive study of the phenomena involved in the deterioration of metals, and also of these rapid laboratory methods for the evaluation of metals for specific service, as now being undertaken by several scientific and technical bodies, has once more focused attention on the "spray test" and particularly the "salt spray test." Regardless of its value or worthlessness as a measure of the performance of a metal under corrosive conditions not involving exposure to the attack of chlorides, its applicability to the study of metals for naval use has not been proved inferior to that of any other method. It is appreciated that service conditions will vary widely with specific applications, that metals aboard ship in some locations may get no spray at all; that some will be subject to alternate wetting and drying and others to continuous immersion; that sometimes frequent cleaning and attention is the rule and that often this is impossible. On the whole, it appears that intermittent spraying and moist atmosphere, without frequent drying or heating (as previously described) is the most satisfactory means of studying the general naval problem, and recent service tests strongly support this assumption.

The reactions taking place in this method of study are of course complex and the ultimate result is a combination of the effect of many factors, chiefly solubility and the electrolytic action of corrosion products in contact with the metal, both as modified by composition and structure. But service also involves these factors so that it is reasonable to assume that the results recorded here are a measure of the stability of the various metals when exposed to the sea without protection and out of contact with dissimilar metals. Where frequent removal of corrosion products is possible, ordinary steels are often satisfactory and stainless metals will not be rapidly introduced. In salt-spray testing, carbon or alloy structural steels usually present the first indications of rust at about the same time as do those stainless steels that also show this effect; only the rapidity and intensity of subsequent action appears to differentiate them.

Three common methods are available for the expression of the results of corrosion tests. These, in the order of ease of application are: appearance of the metals before and after cleaning, loss in weight, and maximum depth to which corrosion has penetrated. For the present tests, time limitations have prohibited the use of the third method, but the other two will, it is believed, satisfactorily convey the conclusions to which the authors have been led.

Steels of Group I.

None of the "hardenable" chromium steels are immune to the attack of the salt spray. All showed the presence of brown flocculent corrosion products shortly after the test began; the spread of the brown film proceeded, however, at widely different rates, in so far as visual examination could determine; the results indicate that the reactions taking place below the surface covering also proceeded more or less vigorously in accordance with the composition and heat treatment of the specimens.

The corrodibility of chromium steels of the cutlery type has been carefully studied in both a qualitative and quantitative way, these researches tending to show that resistance to attack is greater as the proportion of chromium in solid solution is higher, and that it is decreased by the presence of free carbide particles in the microstructure. The latter effect is due not only to the local electrochemical activity between the two dissimilar constituents, but also to the decrease in the concentration of the chromium in the matrix as a result of the precipitation of the carbides from it. The theory should be applicable to all of the steels of this group and of group II, as well as to the steels of the cutlery type; it explains the necessity for heat treatment in steels containing much carbon and also the desirability of the highest permissible chromium content. Little, if anything, however, has appeared concerning the effect of the size of the precipitated carbide particles or the influence of grain size. The tests to be described have been carried out on samples subjected to the same heat treatments as those used in the survey of the mechanical properties in order to note any such effects as well as those due to increased solution of carbides with increase of hardening temperature and if possible to correlate corrosion resistance with the mechanical tests.

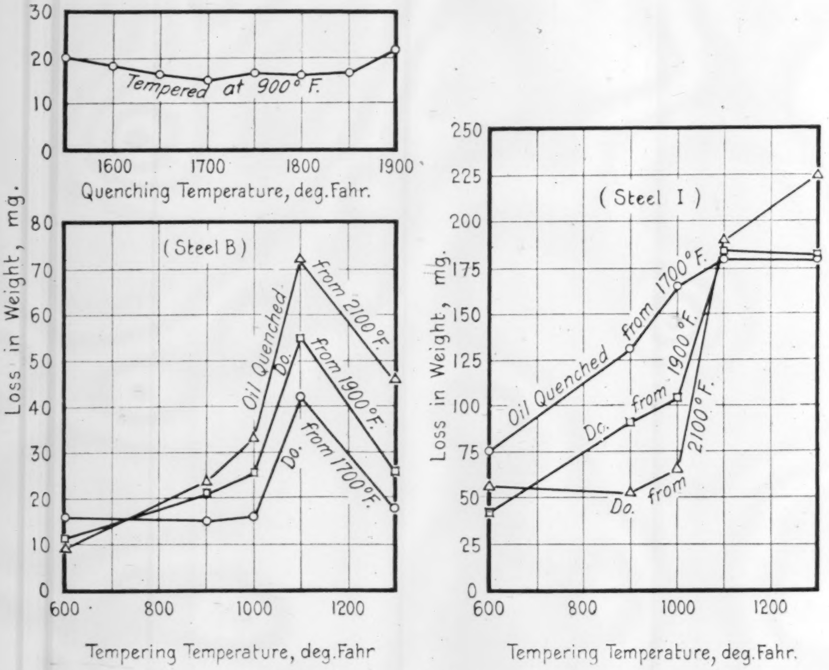
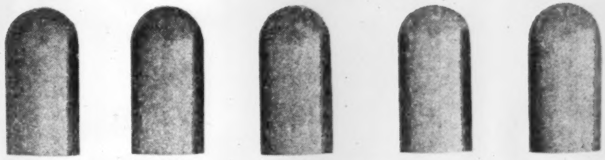
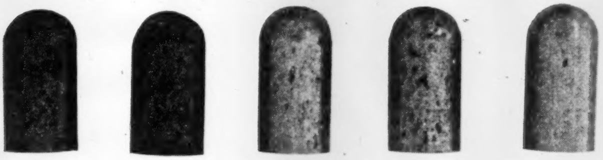


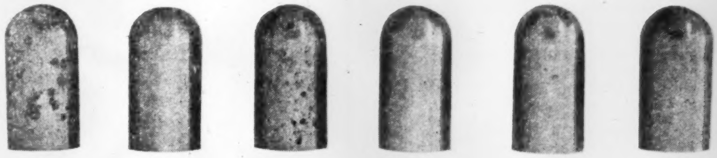
FIG. 13.—Effect of Heat Treatment on Corrosion of Steels B and I.



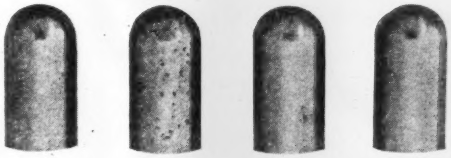
1. Steel B (1700, 600). 2. Steel B (1700, 1100). 3. Steel B (1700, 1300). 4. Steel B (1900, 600). 5. Steel B (2100, 600).



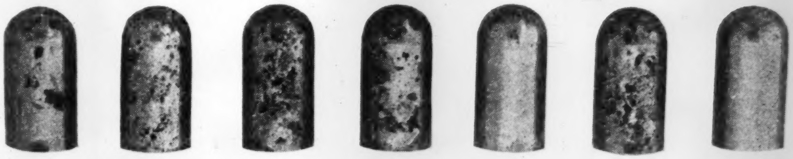
6. Steel G (1700, 600). 7. Steel G (1700, 1100). 8. Steel G (1900, 600). 9. Steel G (1900, 1000). 10. Steel G (2100, 600).



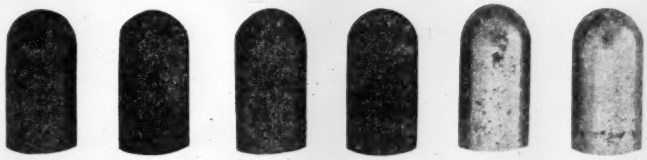
11. Steel K (Annealed). 12. Steel K (1700, 600). 13. Steel K (1700, 1100). 14. Steel K (1900, 600). 15. Steel K (2100, 600). 16. Steel K (2100, 1100).



17. Steel J (1700, 600). 18. Steel J (1700, 1100). 19. Steel J (1900, 600). 20. Steel J (2100, 600).



21. Steel I (1700, 600). 22. Steel I (1700, 1000). 23. Steel I (1700, 1100). 24. Steel I (1700, 1300). 25. Steel I (1900, 600). 26. Steel I (1900, 1300). 27. Steel I (2100, 600).



28. Steel E (1900, 600). 29. Steel E (1900, 1100). 30. Steel F (1900, 900). 31. Steel F (1900, 1100). 32. Steel L (1900, 1100). 33. Steel L (1900, 900).

FIG. 14.—Corrosion Specimens of Group I Steels After Cleaning.

The heat treatment with oil-quenching temperature first and tempering temperature second in deg. Fahr. is given in parentheses under each specimen.

The effect of the temperature of quenching upon the weight loss of steel B in the salt-spray test using specimens tempered at 900° F. is shown in the upper left-hand portion of Fig. 13. Corrosion resistance increases with increase of temperature, is practically uniform over the range of 1650 to 1850° F. and begins to decrease at 1900° F. Tests covering a range of 1700 to 2100° F. for quenching and 600 to 1300° F. for tempering are reproduced at the lower left of Fig. 13. For the lowest tempering temperature, the weight loss due to corrosion decreases slightly with increase of quenching temperature; after tempering at 900° F., the order of superiority of quenching temperatures is reversed and remains so throughout the remainder of the tempering range used. An interesting feature is the maximum loss obtained when tempering at 1100° F. was employed; it is conceivable that in this case, not only the concentration of chromium in the solid solution is concerned but, perhaps to a larger degree, the surface area of the carbide particles as controlled by their number and size. The

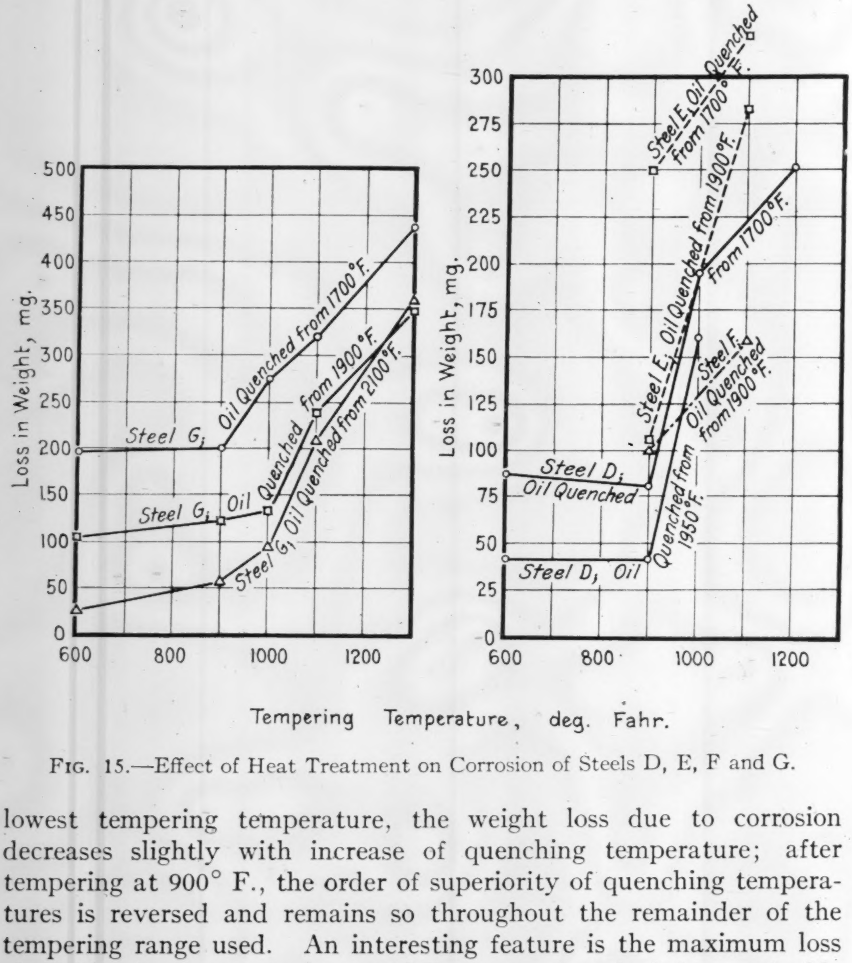


FIG. 15.—Effect of Heat Treatment on Corrosion of Steels D, E, F and G.

appearance of a few of the specimens of steel B after cleaning is shown in the top row of Fig. 14. All of the specimens of this steel were bright after cleaning; all showed small shallow pits, mostly at the top, the number and size being greater when tempering temperatures above 1000° F. were used; the specimens quenched from 1900° F. presented the best appearance. It is naturally difficult to reproduce the finer pits and markings photographically and hence these reproductions should not be used except in conjunction with the descriptive matter.

A few tests of steels D, E and F are recorded at the right of Fig. 15. There is a resemblance to the curves of steel B in the relative uniformity of corrosion loss below 900° F. and the sudden increase between this temperature and 1100° F. Increasing the temperature of quenching, within the limits used, decreases the corrosion loss. The steel with 1.5 per cent of silicon (steel E), when quenched from a temperature productive of only partial hardening, shows only a moderate change in loss due to corrosion over the tempering range in which this change is usually a maximum. After maximum hardness has been developed by quenching, the change is quite as great as in lower-silicon steels of higher chromium content, although the actual losses are higher. Increase of silicon to 3 per cent (steel F) has not greatly affected corrodibility of specimens quenched to give almost maximum hardness, and tempered at a low temperature, but has greatly reduced the change occurring between 900 and 1100° F. The high-chromium steels of this carbon content pit somewhat but are bright after cleaning; steels E and F, however, both pit and discolor. The first four specimens in the bottom row of Fig. 14 are of steels E and F quenched from 1900° F.

As with steel B, the corrosion loss of steel G (Fig. 15) increases more slowly between 900 and 1000° F. than it does above the latter temperature. This follows somewhat the change in tensile strength and hardness in the tempering range of 900 to 1100° F. The resistance to the attack of the salt spray increases rapidly with the quenching temperature but the effect of this temperature decreases as the tempering temperature is raised. Photographs of some of the specimens of steel G are shown in the second row of Fig. 14. Using the quenching temperature of 1900° F., all specimens tempered up to 1000° F. were bright; for the 2100° F. quench, the same was true up to a tempering temperature of 1100° F. To some degree this illustrates the effect of the salt-spray test in relation to the rehardening previously noted. All other specimens of this steel were dull and badly pitted. The best surface condition existed on the specimens quenched from 2100° F. and tempered at 600° F.

Sufficient material was not available for corrosion studies of steel H. The results obtained on steel I are shown on the right of Fig. 13. With the exception of specimens quenched from 2100° F., the weight loss increases steadily with increase of tempering temperature to a maximum at 1100° F.; beyond this temperature, there is no further increase. Those test pieces quenched from 2100° F. showed almost uniform weight losses over the tempering range of 600 to 1000° F. All of the specimens quenched from 1700° F. developed large shallow pits during the corrosion test. For the 1900° F. treatment, the same was true for 1000° F. tempering and above; a similar condition existed in those specimens quenched from 2100° F. and tempered to 1100° F. or higher. When quenching from 1900° F. and tempering at 600° F., a few small pits developed which increased in number on passing to the 900° F. tempering. No pits were observed on specimens quenched from 2100° F. and subsequently tempered between 600 and 1000° F., but at the higher temperature, stains appeared that were not removed in the cleaning operation. Photographs of some of these test pieces appear in the fifth row of Fig. 14.

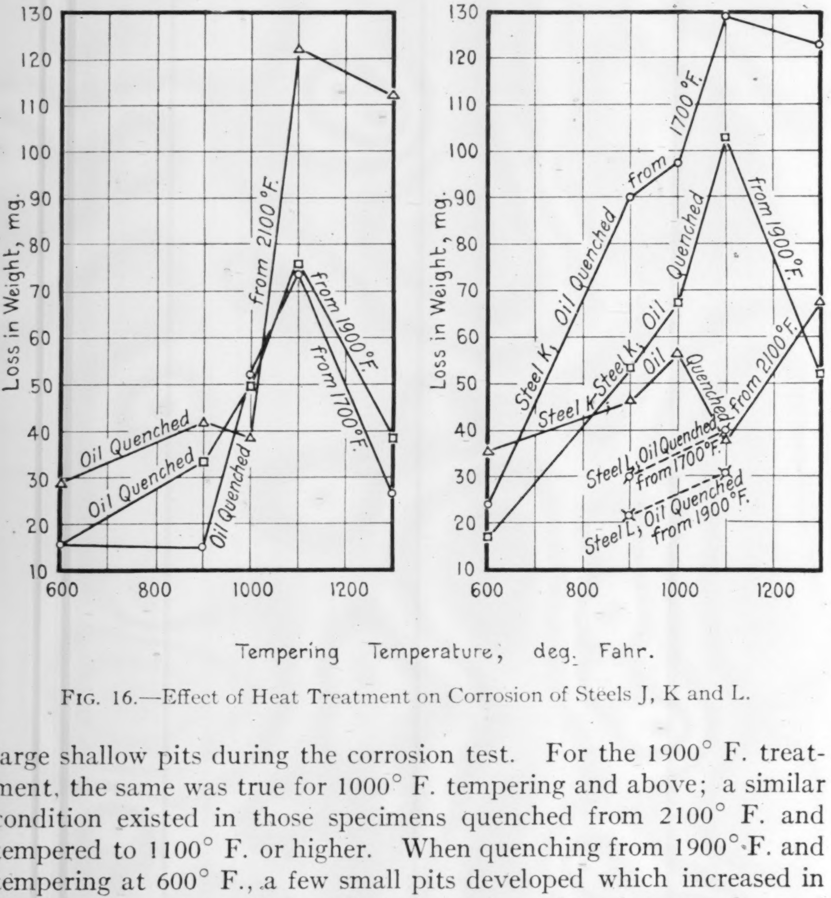


FIG. 16.—Effect of Heat Treatment on Corrosion of Steels J, K and L.

Fig. 16 is a graphical summary of the results obtained on steels J, K and L. The increase of 6 per cent of chromium without change in carbon content (steel J compared with steel I) has produced a great decrease in the weight loss effected by the salt spray. The two series quenched from 1700 and 1900° F. yielded very similar results. Again, as was noted with steel B, there is a distinct maximum weight loss when tempering at 1100° F., particularly for the two lower quenching temperatures. Quenching from 2100° F. produced a marked increase in corrodibility which is most prominent at the higher tempering temperatures. The weight loss of this steel is apparently related to many factors: the chromium content, the progress of carbide precipitation and the rehardening, and the grain size resulting from the temperature and time of heating for hardening. In appearance this steel was exceptionally good, approaching in some specimens the condition of steel B (see fourth row of Fig. 14). With the two lower quenching temperatures, the appearance of the quenched specimens was practically identical for each tempering temperature (using 600 and 900° F. a few very small pits were produced); those tempered at 1000 and 1100° F. developed small, narrow seam-like pits; the 1300° F. specimens were almost as good as those reheated to 600° F. With the 2100° F. quench, tempering up to 1000° F. yielded a similar good condition, 1100° F. a stain not removed by the cleaning operation, and 1300° F. very many small pits.

Steel K produced weight loss curves similar to those of steel J; the effect of the higher carbon content has not been completely overshadowed by the silicon addition, the weight losses being higher than for steel J and the effect of increase in tempering temperature more pronounced. The maximum value when 1100° F. is used for tempering is again in evidence. The curve for specimens quenched from 2100° F. is also of interest because of the sudden change of corrodibility at the temperature at which the sharp rehardening was observed in the mechanical tests. Specimens of this steel are shown in the third row of Fig. 14. After quenching from 1700° F., reheating to 600 to 1000° F. yielded bright specimens containing only a few small pits; with 1100° F. or higher tempering, extensive pitting occurred. The 1900° F. quench produced a very similar condition, with the exception that for like tempering, the pits were smaller and less numerous. When quenching from 2100° F. and tempering at 600 to 900° F., no pits developed but the tension test indicated that these bars were rather soft. Within the range of the rehardening (1000 to 1100° F. tempering) stains appeared on the specimens; with the higher tempering temperature, there was considerable pitting. Steel

L, with 4 per cent more chromium than K, shows lower weight losses and less marked changes on tempering following quenching from 1700 or 1900° F. Two specimens are shown at the lower left of Fig. 14.

These corrosion tests offer numerous difficulties of interpretation created not only by the inherent difficulty of reproduction of results within those small limits of error common to many other forms of testing and the consequent undesirability of basing judgments upon small differences in weight losses but also by the lack, at the time of this writing, of metallographic and other data which may be of unlimited assistance. The tests recorded here do, of course, furnish facts that are of value, but correlation to the desired extent is not possible in every case. Corrodibility of the steels of this group appears to be closely associated with several factors, some of which have been enumerated in the reference to steel J:

1. Carbon, silicon and chromium proportions (other elements undoubtedly affect corrosion resistance but do not appear to play a prominent role in the present tests);
2. The progress of the precipitation of carbides on tempering (there is a possibility of a critical particle size being responsible for maximum corrodibility of the tempered steels);
3. Grain size as varied by the hardening temperature and time at this temperature;
4. Rehardening phenomena produced by suitable combinations of hardening and tempering temperatures, and their relation to the development of structural homogeneity;
5. Carbide masses not in solution following quenching.

Other factors undoubtedly exert an influence. Prominent among these are structural defects such as segregation and non-metallic included particles which are known to produce deleterious effects. These are not considered here although of extreme importance in general practical application of these metals.

The steel containing 7.5 per cent tungsten is different from the others in that corrosion resistance increases with the quenching temperature, over the range used, regardless of the degree of tempering. The large amount of tungsten appears to be responsible, largely perhaps through interference with grain growth at the high temperature. Of the chromium steels, those with high chromium-carbon ratio (steels B and J) show in general the reverse effect in so far as weight loss is concerned; the effect of increased solution of carbides appears to be counterbalanced by other factors. These two steels also show most prominently the peak in the weight loss curves at 1100° F. tempering; it is interesting that the loss of these steels in the annealed state is less than that corresponding to the peaks. The curves for steels I and K (lower ratio of chromium to carbon) are intermediate in general character and for these steels the weight loss in the annealed state closely approaches the maximum values produced by quenching and tempering in the ranges used.

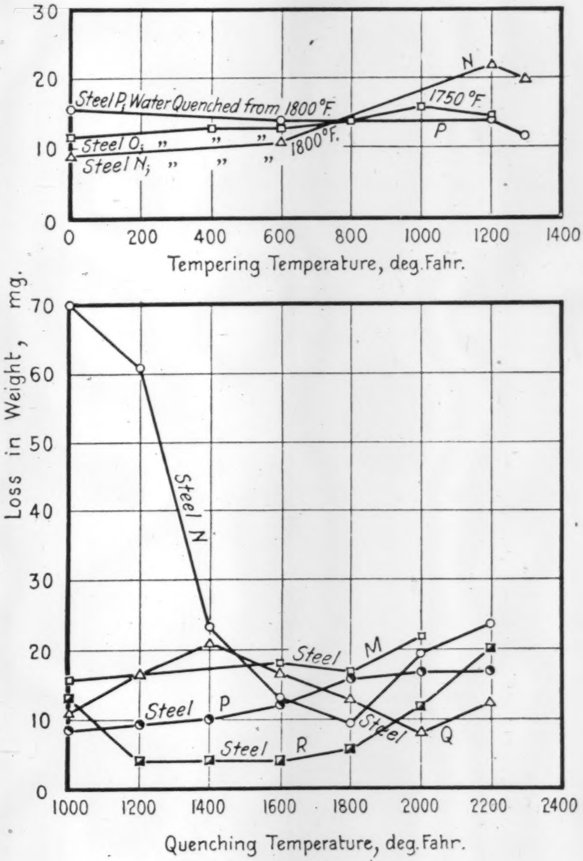
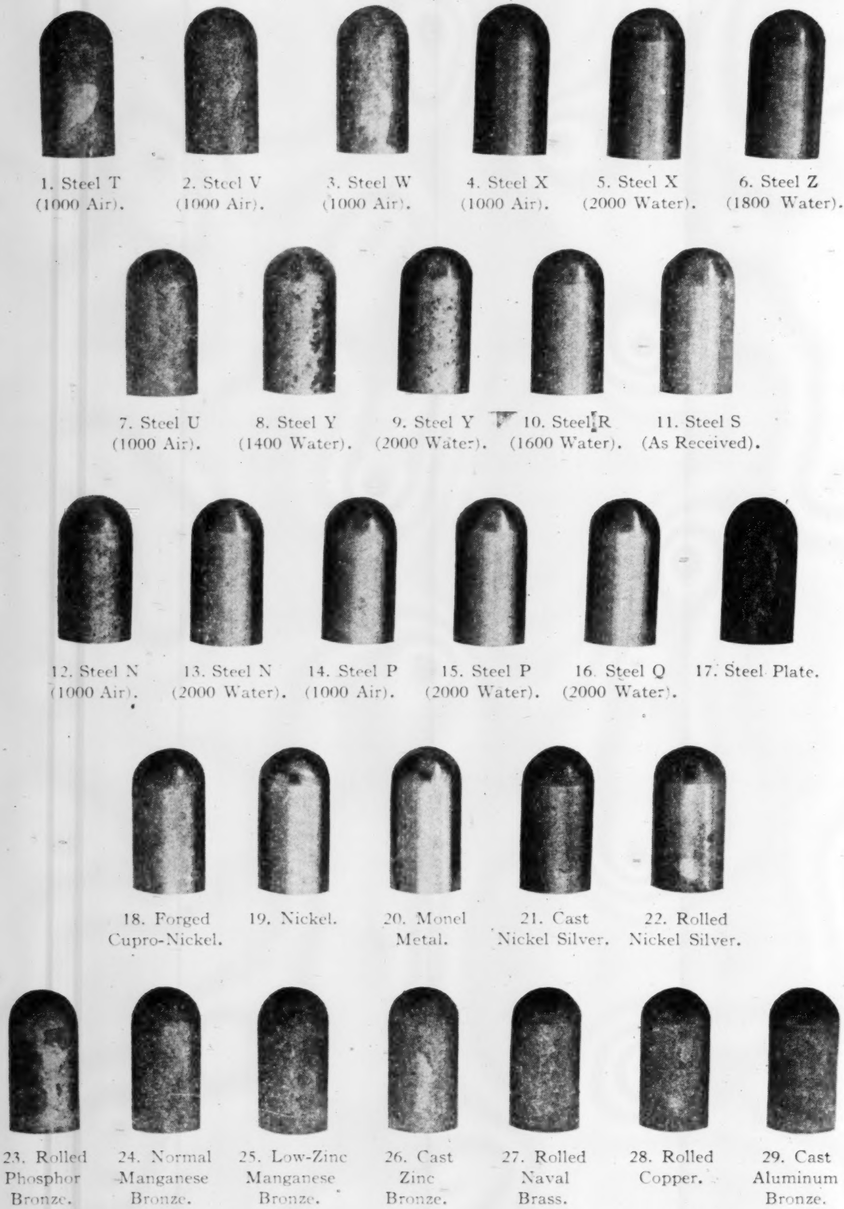


FIG. 17.—Effect of Heat Treatment on Corrosion of Some Chromium Steels.

Steels of Group II.

The lower chart of Fig. 17 contains the results obtained in studying the effect of quenching temperature upon the steels of group II.



1. Steel T (1000 Air).
2. Steel V (1000 Air).
3. Steel W (1000 Air).
4. Steel X (1000 Air).
5. Steel X (2000 Water).
6. Steel Z (1800 Water).
7. Steel U (1000 Air).
8. Steel Y (1400 Water).
9. Steel Y (2000 Water).
10. Steel R (1600 Water).
11. Steel S (As Received).
12. Steel N (1000 Air).
13. Steel N (2000 Water).
14. Steel P (1000 Air).
15. Steel P (2000 Water).
16. Steel Q (2000 Water).
17. Steel Plate.
18. Forged Cupro-Nickel.
19. Nickel.
20. Monel Metal.
21. Cast Nickel Silver.
22. Rolled Nickel Silver.
23. Rolled Phosphor Bronze.
24. Normal Manganese Bronze.
25. Low-Zinc Manganese Bronze.
26. Cast Zinc Bronze.
27. Rolled Naval Brass.
28. Rolled Copper.
29. Cast Aluminum Bronze.

FIG. 18.—Corrosion Specimens of Metals in Groups II and III and Table VII After Cleaning.

The heat treatment in the case of steel specimens is given in parentheses under the specimen.

In dealing with these data, it should be kept in mind that all quenching was done in water, except in the case of the specimens heated after forging, to 1000° F. This treatment was followed by air cooling.

The corrosion loss of steel M is not greatly affected by heat treatment; there is a tendency toward an increased loss when quenching from above 1800° F. It is reasonable to assume that the effects of tempering would be slight, particularly in view of the results obtained with steel O. In this case, with very little more chromium and twice the carbon content, no marked effect is produced in tempering (see upper graph of Fig. 17).

Steel P shows a slight steady rise in corrodibility with increase in quenching temperature, but practically no changes on tempering. All of the test pieces of this steel developed rust but after cleaning were bright with only a very few small pits in evidence. The same is true of steels M and O. Two specimens of steel P are shown in the third row of Fig. 18. As contrasting with steels O and P, steel N, with much lower chromium content, was very greatly affected by thermal treatment. The weight loss due to the salt spray decreases rapidly as the quenching temperature increases to 1600° F. and then slowly to 1800° F.; above this temperature there is a marked increase. On tempering after an 1800° F. quench, the losses are small but nevertheless appreciable. The appearance of two specimens of this steel is illustrated in Fig. 18, at the left end of the third row. All of the specimens were pitted, the degree and the seriousness of pitting following the weight loss curves closely.

Steel Q does not show the advantages that would be expected from its high chromium content, owing perhaps to inability to maintain all of the carbon in solid solution. There is a distinct maximum to the curve for this steel (Fig. 17) at 1400° F. that may bear some relation to the solubility of the carbides. A minimum value of corrodibility by the salt spray appears at the 2000° F. quenching temperature, the same temperature at which maximum hardness developed in the mechanical tests. One of the specimens given this treatment is shown in the third row of Fig. 18. Quenching from this temperature and higher produced test pieces which after cleaning were bright and free from pits but on all those treated at lower temperatures some slight pitting was in evidence.

Steel R is the only alloy of the second group on which all specimens heat treated at temperatures of 2000° F. or below were totally free from pitting. On specimens treated at 2200° F. a few very small pits were developed in testing. It is also interesting to note that many of the test pieces quenched from 1200 to 1800° F. showed no rust-like discoloration throughout the test. Some specimens of this steel that have been tested at other times showed no weighable loss after completion of the test. In a few experiments not recorded here, cooling slowly from between 1800 and 2200° F. produced weight losses no greater than resulted from quenching. Tests of steel S are not shown in the graph but a few specimens tested in the "as received" condition, although rusted by exposure to the salt spray, showed an average loss of only 8 milligrams and no pitting.

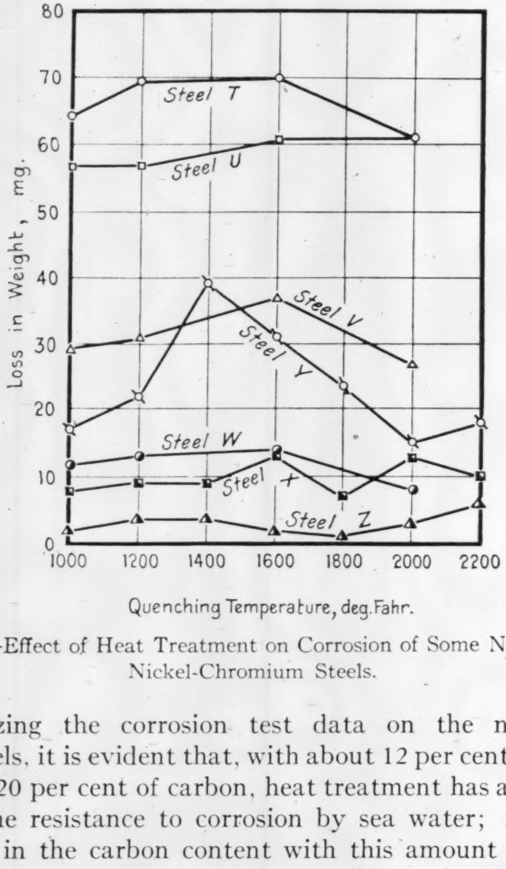


FIG. 19.—Effect of Heat Treatment on Corrosion of Some Nickel and Nickel-Chromium Steels.

Summarizing the corrosion test data on the non-hardening chromium steels, it is evident that, with about 12 per cent of chromium and 0.15 to 0.20 per cent of carbon, heat treatment has a very marked effect upon the resistance to corrosion by sea water; it is believed that decrease in the carbon content with this amount of chromium will reduce the effect but that very low carbon content is required for its elimination. These steels, in their best condition, are subject to some slight pitting. Steels with 15 to 17 per cent of chromium and 0.20 per cent or less of carbon are not greatly affected, in respect to corrodibility, by heat treatment; as with the lower chromium steels, some pitting is always observed. Steels with 20 per cent or more of chromium and about 0.35 per cent or less of carbon will most probably not pit and will show low weight losses in the salt-spray tests; the introduction of copper has a decidedly beneficial effect upon these steels.

Steels of Group III.

The corrosion losses of the nickel and nickel chromium steels are given in Fig. 19. Steel T shows some slight variations in corrodibility with change of quenching temperature. The 35-per-cent nickel alloy U shows practically no variation over the temperature range of 1000 to 2000° F. Both of these steels exhibit no pitting whatever, solution in the corrosive used being uniform over the entire surface leaving a sort of deep etching effect. The condition of the 26-per-cent nickel steel is shown at the left end of the top row in Fig. 18; the other steel is more lightly etched, as is evident from the photograph at the left end of the second row.

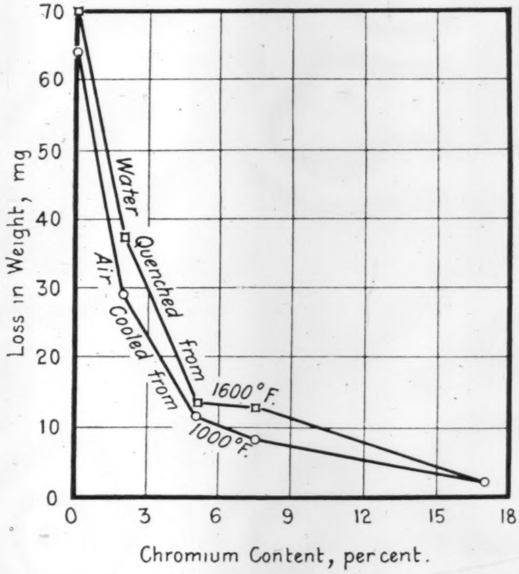


FIG. 20.—Effect of Chromium Content on Corrosion of Some Nickel-Chromium Steels.

The steels containing 2 per cent and 5 per cent of chromium etch in a similar manner but not so deeply as the plain nickel steels (see top row of Fig. 18). The weight losses are continuously less as the chromium content increases and little effect has resulted from heat treatment.

With 23 per cent of nickel and 7 per cent of chromium (steel X) the character of the corrosive attack changes. The specimens assumed a heavy coating of corrosion products during the progress of the test, but after cleaning, although stained, were not deeply etched. A few small pits were scattered over the surface. The staining was somewhat worse on those pieces which had been quenched from 1600 and 1800° F. Two of the specimens are shown in the top row of Fig. 18.

The lower nickel steel (steel Y), containing an equal amount of chromium and no copper, etched in a manner quite similar to the 5 per cent chromium high-nickel steel but in addition developed many small pits on all specimens except those quenched from 2200° F.

TABLE VII.—CORROSION LOSSES OF MISCELLANEOUS METALS IN SALT SPRAY TEST.

Kind of Material	Approximate Chemical Composition, per cent											Loss in Weight, mg.
	C	Mn	Si	Ni	Cu	Sn	Zn	Al	P	Fe	Pb	
Steel Plate	0.15	0.45	...	...	...	...	...	...	...	...	...	1022
Rolled Nickel	...	...	...	99.+	...	...	...	...	...	...	...	7
Monel Metal	1.[a]	2.0	...	67.0	28.0	...	...	...	...	2.0	...	2
Forged Cupro-Nickel	0.1	1.2	0.1	34.3	60.0	...	...	...	...	4.3	...	9
Cast Cupro-Nickel	0.2	0.1	0.4	29.3	63.0	...	...	...	...	7.0	...	11
Cast Zinc Bronze	...	...	...	...	88.0	8.0	4.0	...	...	...	...	23
Rolled Phosphor Bronze	...	...	...	...	95.9	3.9	...	...	0.2	...	...	23
Cast Manganese Bronze	...	3.3	...	...	67.3	...	22.3	5.1	...	2.0	...	51
Cast Manganese Bronze	...	...	...	...	60.6	0.2	38.3	0.8	...	0.1	...	21
Cast Manganese Bronze	...	0.8	...	...	57.7	0.4	39.3	0.7	...	0.8	0.3	29
Cast Aluminum Bronze	...	...	...	...	88.5	...	...	8.5	...	3.0	...	27
Forged Aluminum Bronze	...	...	...	...	88.5	...	...	8.5	...	3.0	...	26
Rolled Silicon Bronze	...	1.2	3.7	...	94.9	...	...	...	...	0.2	...	32
Rolled Copper	...	...	...	...	99.8	...	...	...	...	...	...	11
Rolled Naval Brass	...	...	...	...	60.0	1.0	39.0	...	...	...	...	18
Cast Nickel Silver	...	...	...	15.0	63.0	...	22.0	...	...	...	...	6
Rolled Nickel Silver	...	...	...	15.0	63.0	...	22.0	...	...	...	...	3

[a] Carbon+Silicon.

There is a sharp maximum for the weight loss after quenching from 1400° F. Strangely enough, of the three high-chromium steels, this is the only one which did not develop hardness on long tempering at 1300° F. following high-temperature quenching.

Steel Z with 17 per cent of chromium shows the lowest weight losses of the group and is only slightly affected by heat treatment. The hardness increase at 1300° F. is apparently not accompanied by any marked alteration in the resistance to corrosion; this has been confirmed for two-hour tempering periods (with and without previous quenching) followed by air cooling from the tempering temperature. Some of the samples of this steel remained bright throughout the period of the corrosion test. With quenching temperatures up to 1600° F., some pitting was in evidence; above this temperature no pitting appeared except in those cases (not recorded) in which heating was followed by slow cooling in the furnace.

In Fig. 20, the results of these tests with the steels of group III have been plotted to show the effect of the chromium content for steels containing 23 to 28 per cent of nickel. Variations of composition other than that of chromium are, of course, present and exert some influence. It is believed that this is slight and that any changes to correct for this defect, if it were possible to make them, would shift the points to only a minor degree, leaving the curves in substantially the same form.

In discussing these corrosion tests, specimens offering an extremely wide range of resistance to sea-water corrosion, have been described. Some have been very badly corroded but it should be mentioned here that even the worst do not suffer weight losses equalling that of carbon steel under like conditions. In Table VII, data for common structural steel as well as for a number of the more non-corrodible non-ferrous alloys are given. The properties of monel metal and nickel are rather well known and the results obtained are not surprising. Particularly good resistance to corrosion by the salt spray is possessed by the high-nickel nickel silvers and the cupro-nickel; the latter, in this composition, is rather new in the commercial field. The appearance of many of these metals after the test is shown in the lower portion of Fig. 18.

CONCLUSIONS

Of the "hardenable" chromium steels, none of those studied is totally proof against the ravages of sea-water spray. All far excel common carbon and alloy steels, but all will develop rust regardless of the state of heat treatment, and some pit very badly. Under conditions requiring hardness (for it is only in the hard state that considerable pitting can be avoided) but where a moderate accumulation of corrosion products is not objectionable, or where frequent cleaning of the parts is practicable, certain of the steels investigated are serviceable. But for applications where the accumulation of the products of corrosion is objectionable, all of the steels will be found wanting in some degree. In bearing parts, aside from the reduction of unit loads required by the low hardness and proportional limit, these alloys, although far more resistant to corrosion than ordinary ball steels, still require the protection of lubricating oils and greases. And as the protection of metals by these materials in the presence of sea water is far different under conditions involving frictional motion than when idle, deterioration and damage will ultimately occur, although not as readily, of course, as in the use of the usual ball steels.

A serious drawback to these high-chromium alloys is the low proportional limit. For the hardening types, with the heat treatments used, the ratio of this value to the ultimate strength varies from approximately 0.4 to 0.7 except when using very high quenching temperatures; the value may then drop to 0.1 or lower. Higher values of the ratio are frequently found when employing tempering temperatures beyond 1000° F. For most purposes, hardening temperatures in the vicinity of 1900° F. are to be preferred as yielding the best combination of characteristics.

For structural applications where a thin film of rust that does not penetrate far beyond the visible surface is acceptable, or where frequent cleaning is possible, all of the steels of the second group may be satisfactorily employed. For the best results, steels with chromium under 15 per cent (or perhaps 14 per cent) must be heat-treated prior to use if the carbon content approaches 0.20 per cent. In cases where attention is not possible or convenient and a permanently bright surface is desired, only one steel offers promise and perfect behavior cannot be anticipated in every case. The proportional limit of all of the steels is low but may be modified to some degree by thermal treatment; it varies from approximately 10 or less to 50 per cent of the tensile strength. In spite of their ductility, these steels, with a few exceptions, have generally low impact strength; in one steel a method of greatly increasing this strength has been found.

With respect to the third group, with high-nickel steels containing some chromium, available at prices very slightly higher than the chromium-free types, little use is to be expected of the latter except where considerations other than tensile properties and resistance to corrosion enter as primary factors. These nickel-chromium steels are applicable to the same classes of service as are the steels of the second group. One of the steels will at times be immune to sea-water attack (that is, remain bright) but this is not certain to be true in every instance. Normally, the proportional limit for these steels is very low; only in one case has it been appreciably elevated by thermal treatment, cold working being the only generally applicable method of raising it. The value usually varies from 20 to 50 per cent of the tensile strength. Ductility and impact resistance are very high in all of these steels and commercially practiced methods of increasing the proportional limit do not generally lower it beyond the limits of structural safety.

CORROSION-RESISTANT ALLOYS FOR USE IN ACID MINE WATER[1]

By Robert J. Anderson[2] and George M. Enos[3]

Introduction

In the past several years, tests have been conducted by the U. S. Bureau of Mines on the corrosion of metals and alloys in acid mine waters of coal mines in the western Pennsylvania coal region, and the object of the present paper is to discuss the general corrosion problem as it affects the coal-mining industry and to summarize the results of the Bureau's investigations.

In the coal-mining industry, monetary losses due to corrosion occur in the case of both surface and underground equipment. Corrosion of surface equipment by the atmosphere or other gases will not be considered here, and the loss from corrosion of surface equipment is, on the whole, quite small in comparison with that of underground equipment by the attack of acid water. The failure of pumps and pump parts (rods, valves, etc.), track, pipe lines, and other underground equipment because of the action of acid water causes considerable loss and is a source of much trouble to mine operators. The losses referred to are due not only to the actual replacement costs of the failed parts, but also to enforced shut-downs of part of a mine which sometimes are required when a pump or pipe line fails. Although no figures are available as to the total monetary losses sustained by coal-mine operators because of troubles traced to corrosion, these losses are large, and this special aspect of the general corrosion problem may be properly regarded as important by those concerned with corrosion investigations.

The corrosion of metals and alloys in acid mine waters is a typical example of the failure of engineering materials of construction under attack by corrosive solutions, and in selecting alloys for use in pumping equipment, for example, one of the most important properties for consideration is the corrodibility in the particular mine water encountered. Other factors to be given consideration include the mechanical properties, ease of fabricating or casting, and cost. Tests by the Bureau, both in the field and laboratory, have shown that there are a number of metals and alloys which resist corrosive attack by acid mine water fairly well; a few of these are practically unattacked.

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[1] Published by permission of the Director of the U. S. Bureau of Mines.

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NATURE OF ACID WATER FROM COAL MINES

In order to give an insight into the corrosion problem as it affects the coal-mining industry, it is necessary to discuss briefly the nature of mine water. The underground water from many coal mines is decidedly acid, containing free sulfuric acid, and ferrous, ferric, and aluminum sulfates, as well as sulfates of calcium, magnesium, sodium, and potassium, together with silica, and usually some chlorides. Acidity of mine water is directly due to the presence of free sulfuric acid; such water is also potentially acid from the presence of sulfates of iron and aluminum in large quantities, which may, by hydrolysis, yield free acid. The nature of acid water from coal mines has been studied by Selvig and Ratliff[1] and discussed by Selvig and one of the authors[2] and by the present authors[3] elsewhere, and it need not be given detailed treatment here. Mine water from coal mines will readily corrode ordinary ferrous and non-ferrous materials. In some coal mines, the chloride content is sufficiently high to be a serious factor. Water from metal mines is also frequently corrosive, for example, that of certain copper mines in the West.

The occurrence of iron sulfates and free sulfuric acid in mine water from coal mines is due to the action of water and air on the pyrite or marcasite associated with the coal. These sulfides are oxidized to ferrous sulfate and sulfuric acid, and the reactions may be expressed by the following equations:

$$2\ FeS_2 + 7\ O_2 + 2\ H_2O = 2\ FeSO_4 + 2\ H_2SO_4$$
$$4\ FeSO_4 + 2\ H_2SO_4 + O_2 = 2\ Fe_2(SO_4)_3 + 2\ H_2O.$$

It is well known, of course, that the composition and acidity of mine waters differ with different mines, and also that the water from any particular mine will vary according to the season of the year, the age of the mine, the sulfur content of the coal and gob,[4] and other factors. It is alleged by some that in fairly deep coal mines (*i. e.*, 1200 to 1400 ft.) with correspondingly heavy overburden, the mine water is not so acid as in mines with light overburden, and instances are cited where the corrosion of underground equipment in deep mines was slight as opposed to severe corrosion in shallow mines. However, it is well established that it is the action of air and water on the pyrite in the coal and along the gob which causes the acidity of mine water rather than that the acid water comes from the overburden.

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[1] See paper No. 2 in the appended Bibliography.

[2] See paper No. 3 in the appended Bibliography.

[3] See paper No. 6 in the appended Bibliography.

[4] An abandoned working filled with refuse.

Table I gives the range of composition of acid mine water from bituminous coal mines in the western Pennsylvania coal region and also a typical analysis of water from a specific mine. In general, the free acid may be present in amount from a trace to several thousand p.p.m., and as high as 18,000 p.p.m. has been found. The total acidity varies between wide limits, but it will usually lie between 2,000 and 15,000 p.p.m.

It should be stated that in choosing materials for use in acid mine waters, selection should be based on tests made in the specific water under consideration, since results are variable in different waters.

TABLE I.—RANGE OF COMPOSITION OF ACID WATERS FROM BITUMINOUS COAL MINES, AND ANALYSIS OF A TYPICAL WATER

Constituent	Content, p p.m.[a]		
	Low Value	High Value	Typical Water[b]
SiO_2	16	160	129
Fe^{++}	tr	1 216	516
Fe^{+++}	11	1 303	1 303
Al	trace	1 434	1 225
Ca	79	436	307
Mg	9	197	122
K	0	373	332
Na	21	2 286	512
Cl	0	625	37
$SO_4^{=}$	790	12 115	11 750
Suspended matter[c]	6	91	19
Free acidity[d]	trace	3 662	1 940
Total acidity[e]	2 180	17 200	13 280

[a] Parts per million. (Note.—To convert p.p.m. to grains per U. S. gallon, multiply by 0.0583.)

[b] Filtered water, from the Edna No. 2 mine of the Hillman Coal and Coke Co., at Wendel, Westmoreland County, Pa.

[c] On unfiltered water, dried at 105° C.

[d] Due to free sulfuric acid, in terms of H_2SO_4.

[e] Due to free sulfuric acid plus sulfates of iron and aluminum, in terms of H_2SO_4.

NEUTRALIZATION OF UNDERGROUND WATERS

It has been suggested that mine water should be neutralized by appropriate chemical treatment, thereby removing difficulties caused by acid corrosion and avoiding the necessity of special corrosion-resisting materials. Lime rock and blast-furnace slag have been suggested as suitable neutralizing agents. Neutralization is practical only above ground and here only after the water has already been handled by the pumping equipment. If it is necessary to use the water in the power plant, or if the products of neutralization—iron oxides—have a ready market, the water can be neutralized profitably. Acid mine water cannot be neutralized profitably underground, and there are serious objections to attempting such neutralization: namely, (1) large settling and overflow tanks are required, which would involve considerable extra expense in excavating the space required; (2) water would have to be pumped to one central pump before treating, so that the corrosion of pumping equipment would be only partly eliminated; (3) the neutralizing agent would have to be taken into the mine, and the product of neutralization removed, thus involving considerable extra transportation and hoisting; and (4) the neutralized effluent would have to be filtered.[1]

Neutralization of acid mine water underground may be regarded as quite out of the question, and saving can be made in the replacement of pump parts and pipe lines only by the use of suitable corrosion-resisting materials.

NATURE OF CORROSION PROCESSES IN MINE WATER

The theoretical aspects of the general corrosion problem do not require discussion here, but the general nature of mine-water corrosion may be briefly indicated. Speaking generally, it may be said that when metals or alloys are brought into contact with acid mine water, corrosion will occur if the metal or alloy will react chemically with the acid or salts in the water. This does not imply that corrosive action will necessarily progress beyond the initial stage of attack, since it is well known that films or coatings may be formed on the materials by the interaction, and these may inhibit, or at least retard, the progress of corrosion.

Metals and alloys which resist the action of acid mine water do so because (1) their composition is such that they will not react chemically with the water, or (2) films or coatings are formed which retard or stop the corrosion. The effect of the film or coating is apparent only so long as it is not disturbed by friction or abrasion, or by change in the chemical composition of the water. The question of films and coatings formed upon metals and alloys and their effect upon corrosion in acid mine water has been discussed by the authors[2] in another publication. Possibilities are apparent in the study of alloys which form protective films or coatings, but investigation of this has not proceeded very far to date. At the present time, it is necessary to seek corrosion-resisting qualities in the composition of materials, and some quite good alloys have been developed.

The visual aspects of the failure of metals and alloys by corrosion in acid mine water are very variable, and the usual methods of failure may be indicated. A common way to failure is by a uniform attack or wearing away of the surface, as takes place, for example, with monel metal. Another common method is by pitting, *e. g.*, with aluminum alloys. Embrittlement is sometimes caused, as in naval brass, while sometimes one constituent corroded from an alloy is re-deposited from solution, *e. g.*, with low brass, where copper has been found to re-deposit. Films or coatings may be formed, as has been indicated above. A hard impervious coating may be formed on phosphor bronze, while soft loose coatings may be formed on lead bronze. The visual appearances of various metals and alloys after corrosion in acid mine water have been reproduced in photographs in several published papers.[1]

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[1] See papers Nos. 4 and 7 in the appended Bibliography.

[2] See paper No. 11 in the appended Bibliography.

TESTS BY THE U. S. BUREAU OF MINES

Various tests have been carried out on the corrosion of metals and alloys in acid mine waters by members of the staff of the Bureau of Mines, and the results of these tests are summarized briefly below.

Immersion Tests of Iron and Steel.—In 1920–1921, total immersion tests were carried out by W. A. Selvig for Committee A-5 on Corrosion of Iron and Steel of the Society, on the corrosion of a large number of iron and steel samples of varying composition in acid mine water.[2] The test pieces were 2 by 6 in. in size and of Nos. 16 and 22 gage. The tests were made by immersing the samples in flowing acid mine water at the Calumet mine of the H. C. Frick Coke Co., at Calumet, Pa. The samples were considered to have failed when they had become corroded through or eaten away at the edge for a distance of $\frac{1}{4}$ in. The corrosive action of the mine water on all these samples was severe, and the tests clearly showed that all ordinary grades of iron and steel are corroded rapidly by acid waters from coal mines and that there was no great difference in the rates of corrosion among the commercial varieties of these materials. In all, 49 different irons and steels were tested, and comparison was made between the results obtained in mine water and those obtained on corrosion in atmospheric air. The results were quite different.

Immersion Tests of 45 Metals and Alloys.—In 1921–1922, comparative corrosion tests were made by W. A. Selvig and one of the authors[3] of 45 metals and alloys in acid mine waters at three coal mines in the western Pennsylvania region: namely, the Montour No. 1 Mine of the Pittsburgh Coal Co., at Southview, Washington County, Pa.; the Edna No. 2 Mine of the Hillman Coal and Coke Co., at Wendel, Westmoreland County, Pa.; and the Calumet Mine of the H. C. Frick Coke Co., at Calumet, Westmoreland County, Pa. The materials tested included a variety of ferrous and non-ferrous metals and alloys in the rolled and cast condition. The cast materials were machined to 2 by 6 in. and about $\frac{1}{4}$ in. thick, while the rolled materials were 2 by 6 in. and of about No. 16 gage. The test pieces, in triplicate, were immersed in flowing acid mine water at the three mines in specially designed test boxes which insured even rate of flow and uniform distribution of the water. The conditions of test were maintained as nearly alike as possible at the different mines, the chief variable being the acidity of the waters. The samples were inspected at frequent intervals, and samples that had been corroded through or corroded away at the edge for a distance of about $\frac{1}{4}$ in. were considered to have failed, and were removed. Samples were also removed when they had corroded uniformly and become rather thin. The tests covered a period of 119 days at the Montour No. 1 Mine, 135 days at the Edna No. 2 Mine, and 98 days at the Calumet Mine.

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[1] See papers Nos. 3, 6 and 7 in the appended Bibliography.

[2] See paper No. 1 in the appended Bibliography.

[3] See paper No. 3 in the appended Bibliography

Loss-in-weight data were secured for the metals and alloys after exposure to the corroding action of the waters, and the results may be summarized briefly as follows:

All alloys of the brass type which were tested were corroded severely by the mine waters; the corrosion was uniform (no pitting), and the weight loss large. Bronzes were also corroded considerably, but to a less extent than the brasses, and, within limits, increasing tin appeared to decrease the amount of corrosion in these alloys. At the present time, bronzes are used largely for parts in pumps employed for handling acid water from coal mines. Copper-nickel alloys were corroded in about the same amount as the brasses; the loss in weight was large, and the corrosion was uniform. Nickel silvers (copper-nickel-zinc alloys) of various compositions were badly corroded, the attack in most instances being uniform. Aluminum alloys showed a marked tendency to pronounced pitting; the loss in weight was comparatively small, but the pitting effect precludes the possibility of their use in mine water.

The materials which showed practically no corrosion in the mine waters included a high-chromium steel, two chromium-nickel-silicon steels, a high-silicon cast iron, and a nickel-chromium-iron alloy. All these alloys contained large amounts of chromium, with the exception of the high-silicon cast iron (see Table II for compositions). Commercial nickel corroded very little in the Edna No. 2 Mine water but corroded considerably in the waters from the other two mines.

Taking the materials by groups, the relative corrosion losses may be taken roughly as follows, referring to the Edna No. 2 Mine water: Brasses, 6 to 7 mg. per sq. cm. per day; bronzes, 1 to 3 mg.; copper-nickel alloys, 5 to 7 mg.; nickel silvers, 5 to 7 mg.; aluminum alloys, 2 mg.; high-silicon cast iron, 0.006 to 0.6 mg.; high-chromium steel, 0.0004 mg.; chromium-nickel-silicon alloys, 0.0002 mg.; and nickel-chromium-iron alloy, 0.002 mg. per sq. cm. per day.

Microscopy of Corroded Materials.—In 1922–1923, microscopic study was made of the corroded metals and alloys from the above mentioned investigation. In the long-time immersion tests of the 45 metals and alloys, a number of phenomena were observed in the behavior of the materials, particularly in connection with their rates of corrosion, the formation of surface coatings, selective corrosion, and the relation of chemical composition to corrosion rates and coating formation. In the microscopic study of these corroded materials, the microscopic features of corrosion were observed, and the following conclusions were drawn:

Apparently, grain size has little effect on the rate of corrosion. In alloy systems where there are two or more phases present, there is usually, although not necessarily, one phase that is more resistant to corrosion than the others. This gives rise to selective corrosion. In bronzes, the δ constituent is the more resistant phase; in α-β brass, the α is more resistant. Some alloys, which, after corrosion and subsequent cleaning, appear to be free from adhering coating, have a hard and probably quite impervious coating; this apparently acts as a protection, and is often found on bronzes. In general, corrosion attack does not follow grain boundaries, but proceeds through the less resistant phase in duplex alloys. Microscopic examination of the very resistant alloys revealed no film or coating, and the resistance of such materials is traced to the chemical composition.

The microstructural aspects of materials corroded in acid mine water are shown in photomicrographs in other papers by the authors.[1]

Accelerated Corrosion Tests.—During the progress of the above mentioned investigations, it became increasingly evident that an accelerated test for corrosion which would give results comparable with the results obtained by long-time immersion tests would be of great value in comparing materials for use in mining equipment. Of course, neither long-time immersion tests nor accelerated tests can be absolute criteria of the corrosion to be expected under service conditions, but both such tests do give quite reliable and satisfactory indications as to the nature of the resistance to be expected and some notion as to the probable length of service, provided interfering factors are taken into account. During 1922–1923, investigation was made of the possibility of developing an accelerated corrosion test, and an

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[1] See papers Nos. 5, 6, 8, and 9 in the appended Bibliography.

TABLE II.—CHEMICAL COMPOSITION, PHYSICAL PROPERTIES, AND CORROSION LOSSES OF SOME MATERIALS THAT HAVE BEEN FOUND TO BE RESISTANT TO ACID WATERS FROM COAL MINES

Designation	Chemical Composition, per cent	Corrosion Loss, mg. per sq. cm. per 24 hours[a]		Physical Properties[b]				Remarks
		In Simple Immersion Test	In Accelerated Electrolytic Test	Hardness	Density g. per cc.	Melting Point, deg. Cent.	Tensile Strength, lb. per sq. in.	
FERROUS ALLOYS								
High-silicon cast iron	Si 13.8 C 0.76	0.004	....	49 to 51^c	7.0	1260	10 000	For casting; cannot be worked; machineable only by grinding.
Rolled high-chromium steel	Cr 29.5 Mn 0.27 C 0.36 Si 0.53 Fe remainder	0.00020	15.4	....	7.8	1370	60 000 to 120 000	Can be cast, worked and machined.
Rolled chromium-nickel-silicon steel	Ni 23.87 Cr 12.96 Si 3.40 C low Fe remainder	0.00015	18.5	30 to 65^c	7.76	1480	65 000 to 150 000	Can be cast, worked and machined.
Rolled chromium-nickel-silicon steel	Ni 29.60 Cr 10.73 Si 3.26 C low Fe remainder	0.00074	6.15	30 to 65^c	7.76	1480	65 000 to 150 000	Can be cast, worked and machined.
Cast chromium steel, hard	Cr 18.00 Si 1.00 C 0.65 Mo 0.75 Mn 0.35	....	8.3	....	....	....	....	Can be cast, worked, and machined.
Rolled chromium steel	Cr 13.37 Si 0.87 Mn 0.11 C 0.09	....	0.60	....	....	....	....	Can be cast, worked, and machined.
NON-FERROUS ALLOYS								
Cast lead bronze	Cu 89.8 Sn 9.7 Pb 0.5	2.12	37.4	61 to 70^d	8.6	....	30 000 to 36 000	For casting; can be machined.
Cast lead-zinc bronze	Cu 86.34 Sn 11.24 Pb 0.83 Zn 1.60	0.83	37.1	74 to 83^d	8.6	....	32 000 to 38 000	For casting; can be machined.
Cast lead bronze	Cu 74.9 Pb 14.3 Sn 10.5	1.26	36.0	....	....	....	30 000	For casting; can be machined.
Cast lead bronze	Cu 87.5 Sn 10.6 Pb 1.6	2.56	42.1	61^d	8.6	....	28 000	For casting; can be machined.

[a] Corrosion loss in Edna No. 2 mine water.

[b] Physical properties furnished by manufacturers.

[c] Scleroscope hardness.

[d] Brinell hardness.

TABLE II—(*Continued*)

Designation	Chemical Composition, per cent	Corrosion Loss, mg. per sq. cm. per 24 hours[a]		Physical Properties[b]				Remarks
		In Simple Immersion Test	In Accelerated Electrolytic Test	Hardness	Density g. per cc.	Melting Point, deg. Cent.	Tensile Strength, lb. per sq. in.	
NON-FERROUS ALLOYS								
Rolled complex bronze........	Cu 89.8 .... Pb 4.6 .... Sn 5.6 .. P trace ..	1.70	76.5	37[c]	8.9	....	....	For casting or working; machineable.
Rolled nickel-chromium-iron alloy...........	Ni 57.44 ... Cr 9.37 .... Si 0.55 ... Mn 1.75 .. Fe remainder	0.026	27.55	27 to 30[c]	8.3	1 460	100 000	Can be cast, worked, and machined.
Rolled monel metal.........	Ni 65.1 .... Cu 30.5 .... Fe 4.2	6.72	68.6	162[d]	8.94	1 360	80 000 to 105 000	Can be cast, worked and machined.
Rolled nickel......	Ni 99+....	0.003	53.1	145[d]	8.99	1 450	70 000 to 110 000	For working; machineable.
Cast pure lead.....	Pb 99.99 ...	....	0.85	....	11.00	327	....	For casting or working.
Cast nickel-chromium-tungsten alloy..........	Ni 60...... Cr 20....... W 20.......	....	16.0	....	....	....	....	For casting.

[a] Corrosion loss in Edna No. 2 Mine water.
[b] Physical properties furnished by manufacturers.
[c] Scleroscope hardness.
[d] Brinell hardness.

accelerated electrolytic test devised by the authors and J. R. Adams[1] is described in a published report and in a paper by the authors.[2]

Briefly stated, this test is carried out by making the material to be tested the anode in the solution (mine water) which is the corroding medium, and imposing an electric current of suitable density which will accelerate the corrosion loss over that normally obtained by simple immersion. Platinum wire is used for the cathode. The sample may be rotated, say at 140 r.p.m.; rotation gives an effect analogous to flowing water. A low current density, *e. g.*, about 0.2 ampere per sq. dcm. of surface area exposed, has been used in most of the tests. The sample may be of any convenient size, say 15 to 60 sq. cm. of surface exposed, and can be attached to the rotating spindle (anode connection) of a suitable electrolytic apparatus by means of a copper wire soldered to the sample. The test is run until a sufficient weighable loss is obtained, and for most materials 4 to 8 hours is long enough. The time required to yield a weighable loss will also ordinarily give definite indication of the nature of the corrosion, for example, the kind of coating formed and pitting, if any.

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[1] See paper No. 8 in the appended Bibliography.

[2] See paper No. 10 in the appended Bibliography.

Using this test, accelerated corrosion tests were run on 42 of the metals and alloys previously corroded in the long-time immersion tests, using water from the same three mines. On correlation of the data from both tests, it was found that the order of losses of the 42 materials was roughly the same in both tests, and in the Edna No. 2 Mine water the acceleration secured was such that the test was roughly about 10 times as rapid as the simple immersion test. In the Calumet Mine water, the acceleration was about 40 times as rapid. Hence, depending upon the materials tested, the corroding medium, the time period of exposure, and the current density, and taking account of interfering factors such as protective coatings, it is possible to secure a conversion factor by means of which the results of accelerated electrolytic tests can be translated into terms of long-time immersion tests.

A number of additional alloys not previously tested in the long-time immersion tests were submitted by manufacturers for corrosion test in mine water, and results obtained for these with the accelerated electrolytic test are given in the report by the authors and J. R. Adams.[1]

MATERIALS RESISTANT TO ACID MINE WATER

On the basis of all the above mentioned tests and some others not taken up here, information is available as to the relative corrosion rates of many ferrous and non-ferrous materials in acid mine waters. The mass of data collected in the various investigations is entirely too bulky to permit quoting here, but taking into consideration the loss-in-weight figures, the information secured from visual and microscopic examination of the many corroded samples, and the nature of the films or coatings formed (or their absence) makes possible the selection of a list of materials that are markedly resistant to acid mine waters. Table II gives a list of such materials; the loss data given refer to tests in the Edna No. 2 Mine water, this being typical of very corrosive waters.

It is not claimed that there are no other materials which are resistant to the corrosive action of acid mine waters, but the group given in the table is typical of the various materials which tests and experience have shown are resistant to the chemical, and also (in most cases) to a considerable extent the physical, action of such waters. It should not be inferred that the materials listed are necessarily resistant to attack by dilute sulfuric acid alone (although this is usually the case), since it has been shown that certain constituents of mine water other than sulfuric acid, for example, ferric sulfate, may have a marked effect on corrosion rates.

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[1] See paper No 8. in the appended Bibliography.

The corrosion loss of the high-silicon cast iron and of the chromium-bearing steels is much less than that of most of the nonferrous materials, although lead and certain of the bronzes are quite resistant. Most of the bronzes have the decided disadvantage that their resistance to corrosion is due in large part to the formation of protective coatings. Where it is necessary to use bronze in mining equipment, the bronzes listed in Table II will be found better on the basis of corrosion resistance than a number of others.[1] The nickel-iron-chromium alloy (nichrome) is quite resistant, and this should be found useful for certain parts of equipment. Monel metal has a higher loss in mine water than the other nickel-bearing alloys, but it does not form coatings, the corrosion proceeding uniformly and fairly slowly. Lead, as would be expected, is resistant to the action of acid mine water, and lead is useful for lining pipes, but its softness and malleability are undesirable. The high-silicon cast irons (*i. e.*, duriron) are resistant to the attack of many corrosive media other than mine water, and duriron pumps are used extensively. Duriron has a disadvantage in that it cannot be machined.

While there were some small variations in the corrosion losses of the different chromium-bearing steels, these alloys on the whole are the most resistant to acid mine water corrosion of all the materials tested. Chromium forms with iron a double carbide, and it is presumed that this compound is but slightly, if at all, attacked by acid mine water. In general, the chromium-bearing alloys listed possess physical properties that make them suitable for use in mining equipment. These alloys are, however, expensive.

SOME SPECIFIC CORROSION PROBLEMS OF THE COAL-MINE OPERATOR

Probably the most important problem for consideration is that of the corrosion of pumping equipment.[2] Pumps that may give excellent service under ordinary conditions, where the mechanical strength, workability, and performance are the normal factors to be considered, may not resist the action of acid mine water. Thus, the brass, bronze, and cast iron ordinarily used for pump parts corrode quite rapidly when exposed to such water. In a pump, the valve seat, chamber, pump rod, and other parts are exposed to the water moving with considerable velocity. In many mines, it is necessary to change pump parts every month or six weeks because of failure due to corrosion. It has been fairly common practice to babbitt the chamber and piston, since Babbitt metal resists the action of the water fairly well, although it is soft and abrades easily. Waters carrying considerable suspended silt have a strong abrasive effect, and soft materials are rapidly worn down by such waters. Lead-lined chambers give good service provided the lining hangs tightly to the outer wall and does not permit leaks.

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[1] See papers Nos. 3 and 8 in the appended Bibliography.

[2] See paper No. 7 in the appended Bibliography.

Porcelain-covered plungers have given good service, and, if properly cared for, may be safely substituted for the brass, bronze, or cast-iron plungers commonly used. The porcelain plunger does not corrode, and it presents the additional advantage of minimizing packing troubles, provided it is placed true and level in the pump. If there is any appreciable give or flexure after mounting, the porcelain may crack. The shell of porcelain must be firmly attached and held to the plunger rod. If allowed to run dry, in the pump, the porcelain is liable to overheat and crack. The connections should be made of some suitable acid-resisting material, since otherwise corrosion may cause failure of the connecting part, thereby permitting the shell to loosen and crack. Plunger rods have recently been made of chromium-nickel-silicon steel and have been tried with excellent results.

Another serious problem to the coal-mining industry is the corrosion of pipes used for handling acid water. Unless protected, pipe lines of cast iron, steel, or wrought iron are corroded rapidly by acid mine water. The failure may result from pitting or from a gradual wearing away of the pipe. A common point of failure is at a joint. In order to reduce the replacement of pipe to a minimum, most mining companies are using wood-lined pipes. Lead- or porcelain-lined pipes, and all-wood pipes, having a bituminous coating, are also being used, but not so extensively as the wood-lined iron or steel pipes. There are two types of all-wood pipes: namely, stave pipes and bored pipes. There are disadvantages in the use of any of these types of pipes because, (1) in order to carry the volume of water required, an iron pipe of much larger outside diameter must be used, if it is wood lined; (2) all-wood pipes are not sufficiently strong, and if the wires that hold the staves together are corroded through, the section collapses; (3) lead- or porcelain-lined pipes often leak at the joints and consequently corrode. No satisfactory solution has been made of the pipe problem, but so far, the wood-lined steel or iron pipe finds the greatest application.

Another corrosion problem lies in the failure of tracks; track rails will corrode rapidly if exposed to the action of acid mine water. It is expensive to tear up old track and to buy and install new rails, and the remedy for track corrosion seems to lie in grading the track so that the water will not have an opportunity to come into contact with it. Frequently, this can be done by shooting down the roof and building a ditch line alongside the track.

Mention should be made here of the use of protective paints for coating parts to resist corrosive solutions. There are a number of commercial paint materials which will resist the action of mine water fairly well and will protect parts, provided abrasion or strain does not break the paint coating. Protective paints are widely used, and suitable paints will aid considerably in lengthening the life of certain equipment exposed to acid mine water.

The corrosion of other equipment such as shovels, bars, picks, car wheels, mining machinery, etc., can best be avoided by keeping such equipment away from water rather than by attempting to substitute a corrosion-resistant material.

APPENDIX

Selected Bibliography

1. Report of Sub-committee V on Total Immersion Tests of Committee A-5 on Corrosion of Iron and Steel, *Proceedings*, Am. Soc. Testing Mats., Vol. 21, pp. 157–194 (1921).

2. W. A. Selvig and W. C. Ratcliff, "Nature of Acid Water from Coal Mines and the Determination of Acidity," *Industrial and Engineering Chemistry*, Vol. 14, p. 125 (1922).

3. W. A. Selvig and G. M. Enos, "Corrosion Tests on Metals and Alloys in Acid Waters from Coal Mines," *Bulletin No. 4*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh, Pa. (1922), 71 pp.

4. G. M. Enos, "Acid-Resisting Alloys for Use in Acid Mine Water," *Coal Age*, Vol. 23, pp. 665–668 (1923).

5. R. J. Anderson and G. M. Enos, "Microstructural Aspects of Metals and Alloys Corroded by Acid Mine Water," *Bulletin No. 5*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh, Pa. (1923), 44 pp.

6. R. J. Anderson and G. M. Enos, "Corrosion in Mine Waters, and Recent Investigations of It by the U. S. Bureau of Mines," *Transactions*, Am. Soc. Steel Treating, Vol. 4, pp. 587–610, 647 (1923).

7. G. M. Enos, "The Problem of Corrosion in the Coal-Mining Industry," *Proceedings*, Eng. Soc. of Western Penna., Vol. 39, pp. 309–327 (1923.)

8. R. J. Anderson, G. M. Enos, and J. R. Adams, "Accelerated Corrosion Testing of Metals and Alloys in Acid Mine Water," *Bulletin No. 6*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh, Pa. (1923), 64 pp.

9. R. J. Anderson and G. M. Enos, "Corrosion of Brass as Affected by Grain Size," paper before the Inst. of Metals Div., Am. Inst. of Mining and Metallurgical Engrs., New York meeting, February, 1924.

10. R. J. Anderson and G. M. Enos, "An Accelerated Electrolytic Corrosion Test," *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part II[1] (1924).

11. R. J. Anderson and G. M. Enos, "Coatings Formed on Corroded Metals and Alloys," paper before the Inst. of Metals Div., Am. Inst. of Mining and Metallurgical Engrs., Milwaukee meeting, October, 1924.

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[1] The present volume, see Table of Contents.—Ed.

ENDURANCE PROPERTIES OF CORROSION-RESISTANT STEELS[1]

By D. J. McAdam, Jr.[2]

This paper gives the results of an investigation of endurance properties of corrosion-resistant steels at the U. S. Naval Engineering Experiment Station. The present investigation is part of the general investigation of endurance properties of metals that has been carried on at the Naval Experiment Station for several years and has been described in previous papers (**1**,**2**).[3] In studying the endurance properties of corrosion-resistant steels, endurance tests have been made by the rotating cantilever method and by the alternating-torsion method. The endurance properties thus obtained have been compared with the results of static tension and torsion tests.

Testing Apparatus

Rotating Cantilever Testing Machines.—The machines used in the rotating cantilever endurance tests were developed at the Naval Experiment Station. They were described in a preceding paper(**1**).

Alternating-Torsion Testing Machine.—The alternating-torsion tests were made on a machine of the inertia type developed at the Naval Experiment Station and described in a previous paper(**3**). In this machine the inertia of an oscillating flywheel causes alternating torque in the specimen. The torque varies as the moment of inertia of the flywheel, as the amplitude of oscillation of the flywheel, and as the square of the frequency of oscillation. In the machines used, the torque may be adjusted by varying the inertia of the flywheel by adding to it rings of known moment of inertia, by varying the radius of crank-pin motion, or by varying the frequency of oscillation. The upper limit of practicable frequency in this machine is 2150.

Endurance Test Specimens

Rotating Cantilever Specimen.—The specimen used in the rotating cantilever endurance tests, though essentially the same as that described in previous publications(**1**,**2**), has been changed somewhat. As in the original specimen, the taper is such that the stress is uniform within about 1.5 per cent over a length of $1\frac{1}{2}$ in. and the plane of maximum stress is $\frac{3}{4}$ in. out from the fillet. The tapered portion in the new specimen, however, has been made somewhat shorter than in the original specimen so that it is now only 2 in. long (see Fig. 1). This is long enough to avoid danger of breaking at the outer fillet.

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[1] Published by permission of the Secretary of the Navy.

[2] Metallurgist, U. S. Naval Engineering Experiment Station, Annapolis, Md.

[3] The boldface numbers in parentheses refer to the papers given in the list of references appended hereto, page 303.

Alternating-Torsion Specimen.—The specimen used in the alternating-torsion tests is shown in Fig. 2. It is of different type from the specimen used in alternating-torsion tests described previously(2).

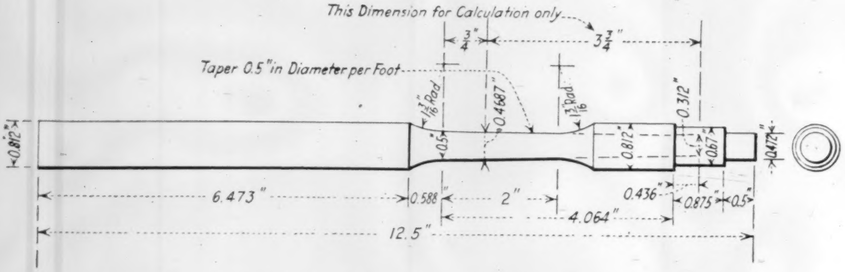
This Dimension for Calculation only
3/4"
3 3/4"
Taper 0.5" in Diameter per Foot
1 3/16" Rad.
0.4687"
1 3/16" Rad.
0.312"
0.812"
0.5"
0.812"
0.67"
0.472"
6.473"
0.588"
2"
0.436"
0.875"
0.5"
4.064"
12.5"

FIG. 1.—Rotating Cantilever Specimen, Type Cc-9.

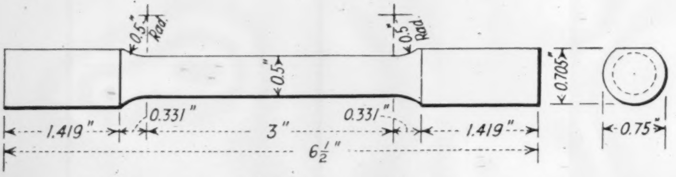
0.5" Rad.
0.5" Rad.
0.5"
0.705"
0.331"
0.331"
1.419"
3"
1.419"
6 1/2"
0.75"

FIG. 2.—Alternating-Torsion-Specimen, Type R.

In the old specimen, which was used in endurance tests by the fatigue method, the effective test length was very short. In the new specimen the effective test length has been increased to provide for tests by the deflection method and by the accelerated fatigue method described below.

Surface Finish of Endurance Test Specimens.—The method of machining and polishing these specimens was the same as that designated in a previous paper(2) as Polish 9. The specimens, preparatory to polishing, were smooth turned to within 0.010 in. of the finished diameter. The finishing tool had a radius of $\frac{1}{2}$ in., the speed of the lathe was 90 r.p.m. and the feed was 130 threads per inch. The finishing process consisted in alternate longitudinal and circumferential polishing, first with emery cloth and then with flour of emery. The circumferential polishing was done by the edge of a cloth-covered, relatively thin, rapidly revolving disk moved slowly along the specimen. Longitudinal polishing was done by a rapidly revolving cloth-covered cylinder with axis in a plane perpendicular to the specimen; in polishing, the cylinder was moved slowly along the specimen. Polishing by this method, which is rapid, was continued until no circumferential scratches were visible at a magnification of 50.

Details of the polishing process are as follows: No. 000 emery cloth longitudinally, 3 minutes; flour of emery circumferentially, 3 minutes; flour of emery longitudinally, 3 minutes.

MATERIAL

The Crucible Steel Co. of America, the Halcomb Steel Co., the Carpenter Steel Co., and the Firth-Sterling Co. generously cooperated in this investigation by furnishing material in the form of round bars about 1 in. in diameter. Instead of the trade name, a letter is used to designate the kind of material. The chemical composition and designation of each material are given in Table I.

Table I.—Chemical Composition of Bar Material.

All values in per cent.

Material Designation	Carbon	Manganese	Phosphorus	Sulfur	Silicon	Nickel	Chromium	Vanadium	Copper
A[a]	0.08	0.07	0.017	0.007	0.11	.....	11.78	.....	0.05
I	0.42	0.27	0.016	0.058	0.56	0.20	12.26	.....	0.04
J	0.40	0.28	0.017	0.058	0.59	0.18	15.21	.....	None
B	0.61	0.39	0.018	0.035	0.03	0.24	15.81	.....	1.10
K	0.85	0.39	0.020	0.005	0.16	0.26	14.99	None	0.03
C	0.24	0.80	0.010	0.027	1.65	22.90	5.42	.....	0.78
D	0.45	0.49	0.012	0.022	1.39	28.20	8.38	None	0.67
G	0.38	0.71	0.020	0.048	2.36	15.88	15.95	.....	0.08
H	0.80	0.86	0.017	0.045	1.70	12.19	19.01	.....	0.05
F	0.39	0.66	0.018	0.030	1.44	25.27	17.71	.....	0.12
E	0.70	0.72	0.018	0.060	3.08	25.81	17.32	.....	0.05

[a] Chemical composition as given by manufacturers.

Note.—Unless otherwise stated, analyses were made at the Engineering Experiment Station.

As listed in Table I, these corrosion-resistant steels may be divided into three groups. The first group, Materials A, I, J, B, and K, includes high-chromium or "Stainless" steels varying in carbon content from "Stainless Iron" having 0.08 per cent carbon to a stainless steel having 0.85 per cent carbon. The second group, materials C and D, includes steels of high nickel content and intermediate chromium content. The third group, materials G, H, F, and E, includes steels of high nickel and high chromium content.

HEAT TREATMENT

The material had been annealed by the manufacturers. The high-nickel steels were tested as received from the manufacturers.

The stainless steels were heat treated at the Naval Experiment Station. An electric muffle furnace was used and the specimens were supported so that there was an air space between them and the bottom of the furnace. The temperature of the outermost bars of a set being heat treated was found to differ not more than 5° F. from that of the bars in the midst of the set.

The heat treatments given to the various kinds of material are described in detail in Table II. In this table, a designation is given to each material according to its composition and heat treatment. For example, material K-10 has the composition K as recorded in Table I, and has received the heat treatment described in Table II. Materials C, D, G, H, F, and E are not included in this table since they were not heat treated at the Naval Experiment Station but were tested in the annealed condition as received from the manufacturers. In this table and in the tables and graphs that follow, the letter "*r*" is added to the composition letter to indicate that the material was tested as received from the manufacturers.

TABLE II.—HEAT TREATMENT.

Material Designation	Heat Treatment					
	Heated to —deg. Fahr.	Time Held, hr.	Cooled in	Reheated to —deg. Fahr.	Time Held, hr.	Cooled in
A-09	1800	$1\frac{1}{2}$	Oil	900	2	Air
A-010	1800	"	"	1000	"	"
A-011	1800	"	"	1100	"	"
A-013	1800	"	"	1300	"	"
A-1	1800	2	Furnace	....	..	....
I-10	1650	1	Water	1000	1	Air
I-12	1650	"	"	1200	"	"
I-1	1650	"	Furnace	....	..	....
J-9	1650	1	Water	900	1	Air
J-10.5	1650	"	"	1050	"	"
J-12	1650	"	"	1200	"	"
J-1	1650	"	Furnace	....	...	....
J(*r*)[a]	....	..	....	....	..	....
B-9	1650	1	Water	900	1	Air
B(*r*)[a]	....	..	....	....	..	....
K-9	1650	1	Water	900	1	Air
K10.5	1650	"	"	1050	"	"
K-12	1650	"	"	1200	"	"
K(*r*)[a]	....	..	....	....	..	....

[a] Annealed by manufacturer.

NOTE.—Unless otherwise stated material was given final heat treatment at the Naval Engineering Experiment Station.

TENSION TESTS

In Table III are given the results of tension tests. For convenience, the results from material of the same composition are grouped together and arranged in definite order, according to heat treatment. For each material, the sequence is as follows: Quenched material, arranged in order from lowest to highest temperature of draw; annealed material. The same sequence is used in tables and graphs to be described later.

Unless otherwise indicated, all the results given in the table were obtained with Navy standard tension test specimens of 2-in. gage length. Two tension specimens were of 12-in. gage length and ½-in. diameter. These had been prepared for a special investigation not directly connected with the investigation of endurance properties. Results obtained with these two long specimens are recorded in the table because, for the material represented by them, on results obtained with standard specimens are available.

TABLE III.—RESULTS OF TENSION TESTS.

Material Designation	Cooled in	Drawn at —deg. Fahr.	Tensile Strength, lb. per sq. in.	Johnson's Limit, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent
A-09..........	Oil	900	166 500	35 000	24 500	24 500	18.0	58.5
A-010........	"	1000	164 600	72 000	25 000	60 000	17.0	61.6
A-011........	"	1100	109 500	None	None	63 000	20.5	70.0
A-013........	"	1300	83 250	51 000	43 000	45 000	27.0	74.0
A-1...........	Furnace	....	63 250	21 000	20 000	21 000	40.0	72.0
I-10..........	Water	1000	171 500	88 000	27 500	....	11.0	41.0
I-12..........	"	1200	121 500	83 000	56 000	....	15.0	52.2
I-13[a]........	"	1300	98 000	37 500	32 500	....	27.0	58.5
I-1[a]..........	Furnace	....	82 000	37 000	35 000	....	36.5	64.6
J-9...........	Water	900	164 300	112 000	72 500	111 000	11.5	38.4
J-10.5........	"	1050	123 250	None[b]	None[b]	....	13.0	48.3
J-12..........	"	1200	115 700	59 500	51 750	55 000	20.0	54.2
J-1...........	Furnace	....	91 700	39 000	20 000	....	28.0	61.4
J(*r*)[a]	As received		110 000	47 500	22 500	32 000	24.0	53.5
B-9..........	Water	900	199 500	133 000	119 000	....	9.0	13.0
B(*r*)	As received		99 750	50 000	25 000	....	28.0	48.5
K-9..........	Water	900	230 300	140 000	70 000	135 000	5.0	8.6
K-10.5........	"	1050	167 640	109 000	67 000	....	7.5	21.8
K-12.........	"	1200	131 500	77 000	51 000	....	12.0	30.5
K(*r*)	As received		111 000	42 000	22 500	24 000	17.5	32.7
C(*r*)..........	As received		96 000	42 000	25 000	38 000	33.0	59.8
D(*r*)..........	As received		111 100	52 500	22 750	....	24.0	48.9
G(*r*)..........	As received		130 000	57 000	35 000	....	24.5	37.5
H(*r*)	As received		123 000	49 500	30 000	....	21.0	27.0
F(*r*)..........	As received		118 250	54 500	30 000	....	21.5	33.0
E(*r*)..........	As received		106 500	45 000	20 000	....	12.0	15.0

[a] Gage length, 12 in.
[b] Stress-strain diagram curved from origin.

Stress-strain curves representing results of tension tests are shown in Figs. 3 to 8, inclusive. These graphs were used to determine the values for proportional limit and Johnson's limit given in Table III. In the case of some of these curves, only a small portion is approximately straight. The graph representing material J-10.5 of Fig. 5 is decidedly curved throughout its entire length. After the abnormality of these curves was noticed, the elastic limit (the lowest stress producing permanent deformation) was determined in testing each of the remaining specimens. The elastic limits thus obtained have been marked on the appropriate curves and the values have been recorded in Table III. On each curve, there has also been

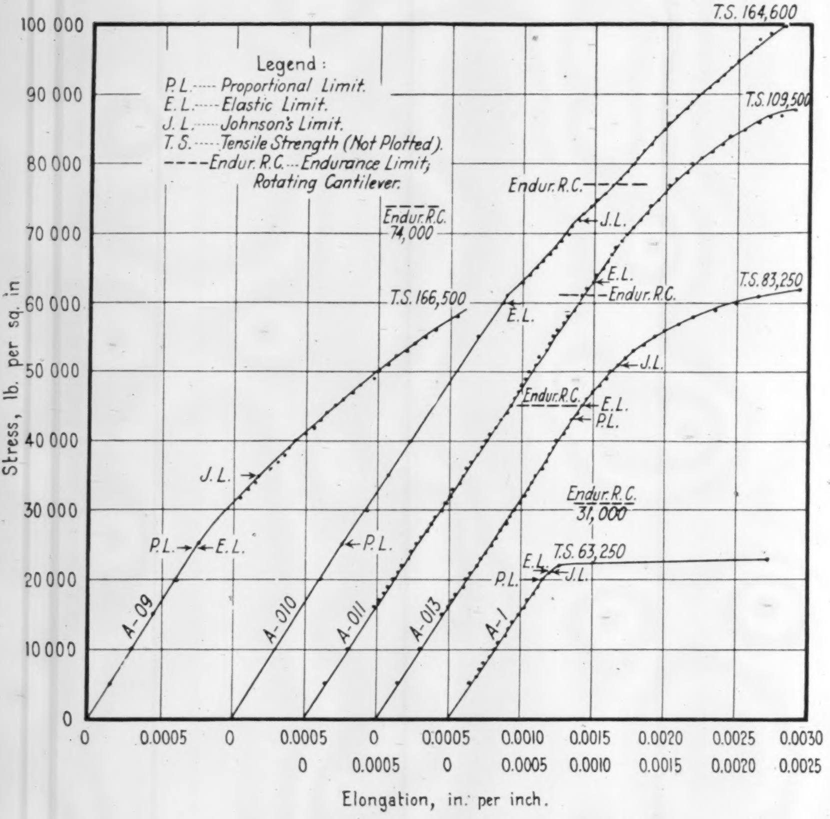

FIG. 3.—Tensile Stress-Strain Diagrams, Material A.

marked the rotating cantilever and alternating-torsion endurance limits determined as described below.

Description of Figs. 3 to 8, inclusive.—Fig. 3 shows the tension test results obtained with "Stainless Iron," material A. In the graph for material A-09, the straight portion is very short. The proportional limit is about the same as the elastic limit and is only about one-seventh the tensile strength. Material A-010, which was drawn at

1000° F., has about the same tensile strength as material A-09, which was drawn at 900° F. The graph for material A-010 is slightly curved from the origin. Below the point selected as the proportional limit, however, the curvature is so slight that this portion of the curve may be assumed to be straight. The proportional limit thus determined is less than one-half the elastic limit and less than one-sixth the tensile strength. The elastic ratio is lower than one would expect to find in material that had received this heat treatment. The graph

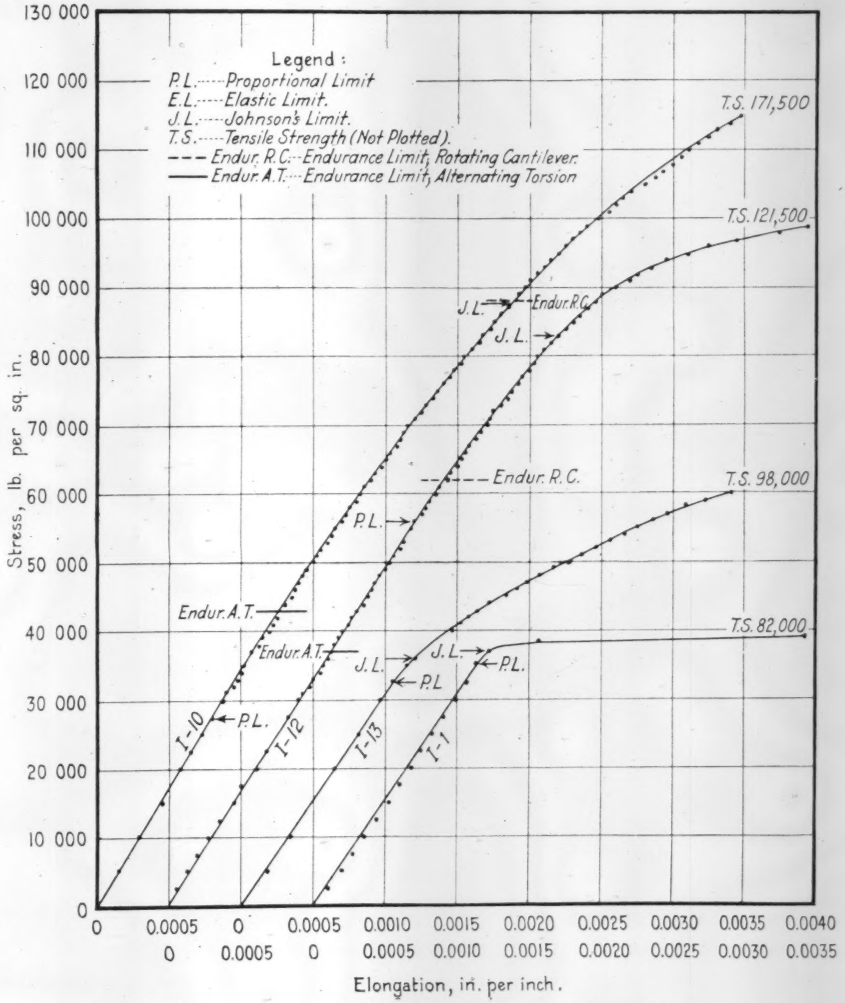

FIG. 4.—Tensile Stress-Strain Diagrams, Material I.

representing material A-011 is curved throughout its entire length. The elastic ratio of this material is high, though it is not so high as would be expected in an alloy steel that had received this heat treatment. The elastic ratios of materials A-013 and A-1 are low. In each of these steels the proportional limit is practically the same as the elastic limit.

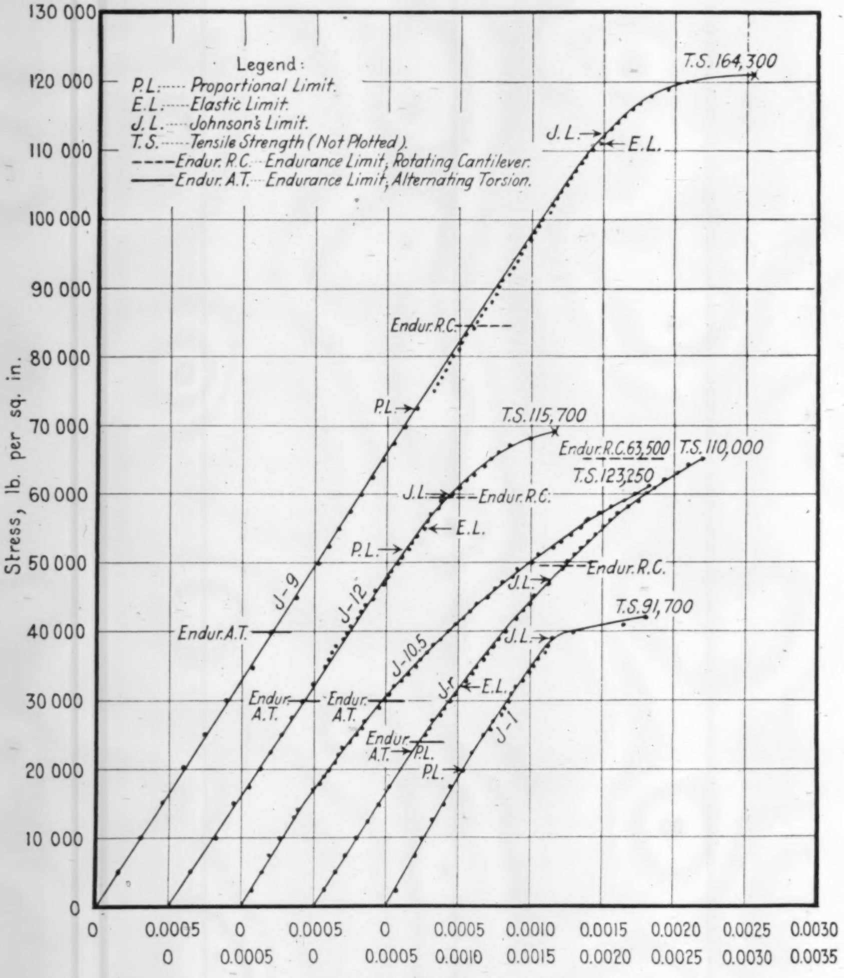

FIG. 5.—Tensile Stress-Strain Diagrams, Material J.

Fig. 4 illustrates the tension test results obtained with material I. Though the graph for material I-10 is probably curved from the

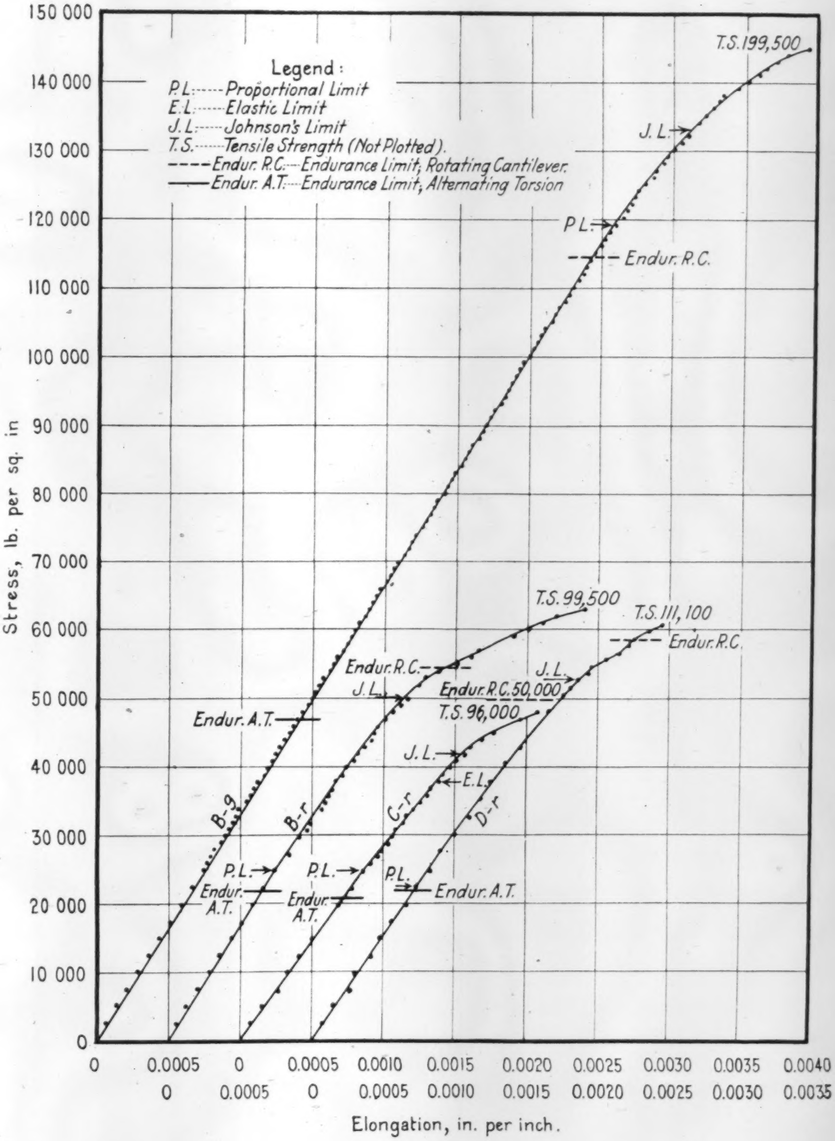

Fig. 6.—Tensile Stress-Strain Diagrams, Materials B, C and D.

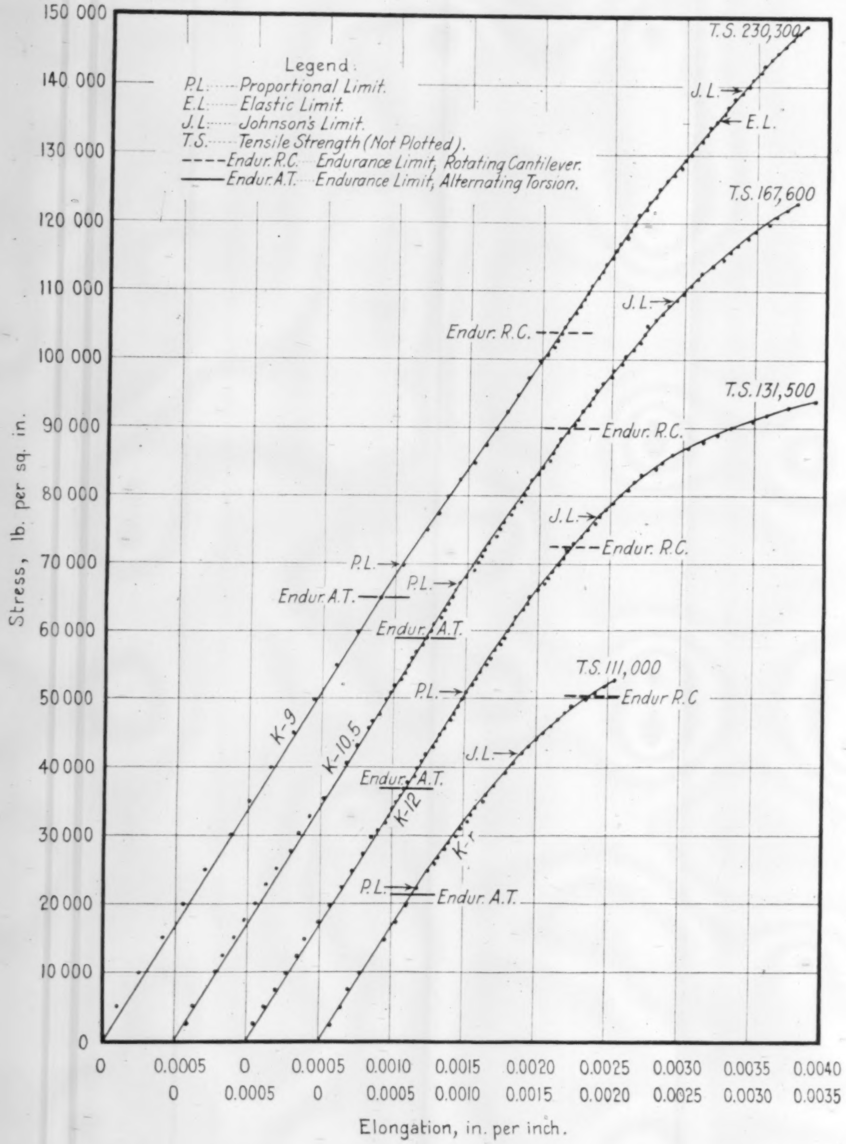

FIG. 7.—Tensile Stress-Strain Diagrams, Material K.

origin, the curvature below the point selected as the proportional limit is so slight that this portion of the graph may be assumed to be straight. The proportional limit is even below the alternating-torsion endurance limit. It is less than one-third the value for Johnson's limit and less than one-sixth the tensile strength. The proportional limit for material I-12 is lower in proportion to the tensile strength than is usual in quenched alloy steels. The proportional limits of materials I-13 and I-1 are low in proportion to their tensile strength.

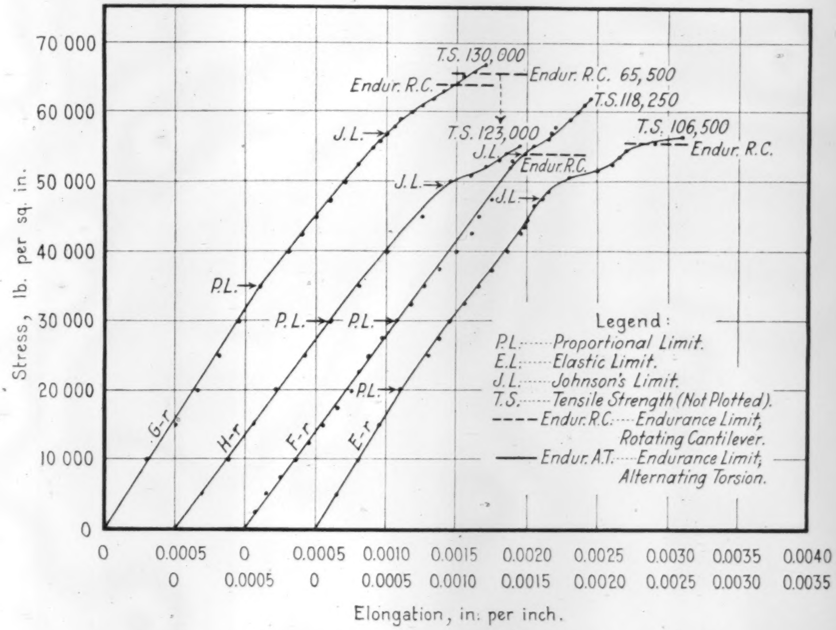

FIG. 8.—Tensile Stress-Strain Diagrams, Materials G, H, F and E.

Fig. 5 illustrates the tension results obtained with material J. Material J-9 has a lower proportional limit in comparison with its tensile strength than is usual in quenched alloy steels. The elastic limit of this material is 50 per cent higher than the proportional limit and practically coincides with Johnson's limit. The elastic ratio, as would be expected in a quenched alloy steel, is high. The elastic limit of material J-12 is only slightly higher than the proportional limit and the elastic ratio is lower than one would expect to find in heat-treated alloy steel. Material J-10.5 shows no proportional limit. The proportional limits of materials J and J-1 are only about one-fifth the ultimate stresses. The elastic limit of material J is about 50 per cent higher than the proportional limit. The elastic ratio, nevertheless, is low.

Fig. 6 shows tension results obtained with materials B, C, and D. Material B-9 has a comparatively high proportional limit, although not so high as one would expect to find in an alloy steel that had received such heat treatment. Materials B, C, and D have very low proportional limits. The elastic limit of material C is 50 per cent higher than the proportional limit. The elastic ratio, nevertheless, is low.

TABLE IV.—RESULTS OF STATIC TORSION TESTS.

Material Designation	Cooled in	Drawn at —deg. Fahr.	Nominal Torsional Strength, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Angle of Twist per Linear Inch at Proportional Limit, minutes	Angle of Twist per Linear Inch at Break, deg.
I-10	Water	1000	110 490	None[a]	....	49
I-12	"	1200	83 320	56 150	40.0	178
J-9	Water	900	110 490	82 100	60.0	43
J-10.5	"	1050	93 290	45 900	31.6	140
J-12	"	1200	73 360	24 150	18.3	178
J(*r*)	As received		70 640	None[a]	....	242
B-9	Water	900	118 650	89 350	63.3	26
B(*r*)	As received		76 080	31 400	21.6	171
K-9	Water	900	150 350	118 340	83.3	19
K-10.5	"	1050	129 970	62 800	46.6	10
K-12	"	1200	87 170	60 370	45.0	91
K(*r*)	As received		84 230	36 230	25.0	122
C(*r*)	As received		69 290	24 190	20.0	323
D(*r*)	As received		72 810	31 750	28.3	162
G(*r*)	As received		84 680	23 550	16.6	150
F(*r*)	As received		74 270	41 050	36.6	137
E(*r*)	As received		81 060	None[a]	....	109

[a] The moment-strain graph was curved throughout its entire length.

Fig. 7 shows results obtained with material K. The graph for material K-9 is apparently curved slightly from the origin. Below the point indicated as the proportional limit, however, the curvature is slight. The elastic limit is nearly twice the proportional limit, and practically coincides with Johnson's limit. The elastic ratio, nevertheless, is lower than one would expect in an alloy steel that had received such heat treatment. Materials K-10.5 and K-12 have low proportional limits. Though the curve for material K is apparently curved from the origin, the curvature below the point selected as the proportional limit is slight. The proportional limit of this material is only about one-sixth the tensile strength.

Fig. 8 shows results obtained with materials G, H, F and E. In these steels the proportional limit is not more than one-fourth or one-fifth the tensile strength.

Torsion Tests

Results of static torsion tests are given in Table IV. For these tests a specimen having a 3-in. gage length and $\frac{3}{4}$ in. in diameter was used. To obtain the values for proportional limit given in Table IV, graphs were plotted in which ordinates represented torsional moments and abscissas represented angles of twist. From the proportional limits obtained from such graphs, the values for proportional limit in pounds per square inch were calculated. A comparison of these values with the corresponding values for proportional limit in tension as given in Table III makes it evident that in these corrosion-resistant steels the proportional limit is of little significance.

Rotating Cantilever Endurance Tests

General Description of Tests.—The speeds of the various units of cantilever endurance testing machines at the Naval Experiment Station range from 1200 to 1800 r.p.m. The weights that cause the test stresses are suspended by springs. The machines are so arranged that the load can be applied after a machine reaches full speed and is automatically removed if the speed slackens below a certain point or if the machine stops. This provision was found necessary, especially in testing specimens the endurance limit of which is near the proportional limit. Whenever possible, a test on any specimen was continued without stopping the machine until the specimen broke or was removed.

Since not more than three specimens were available to represent each composition and heat treatment, attempt was made to get an approximate indication of the endurance limit by means of the first specimen of each set. For this purpose, in beginning the test, the specimen was stressed to some point below the estimated endurance limit. After about 150,000 to 200,000 cycles, this stress was increased about 2000 or 3000 lb. and the specimen was subjected to an additional 150,000 to 200,000 cycles and the stress was again raised 2000 or 3000 lb. This process was repeated until the specimen broke. From the result thus obtained an estimate was made of the proper stress to use in testing the second specimen of the set.

Graphic Summary of Results.—Tabulated results of endurance tests are not included since it is believed that the results are better presented graphically. Results are summarized in Figs. 9 to 14, inclusive.

In these graphs semi-logarithmic plotting has been used. Figs. 9 to 13 each represent material of only one composition, heat treated in various ways. In Fig. 14 are shown results obtained with the high-nickel steels tested in the annealed condition as received from the manufacturers.

The meanings of the various marks used in these graphs are as follows:

An open circle indicates that the specimen was tested throughout and broke at the indicated stress.

An open circle crossed by diagonal lines indicates that the specimen was subjected to the indicated number of cycles at the indicated stress and the stress was then increased.

An open circle crossed by a vertical and a horizontal line indicates that the specimen was removed after being subjected to the indicated number of cycles at the indicated stress.

A solid circle indicates that the specimen, previously tested at a lower stress, broke at the indicated stress and number of cycles.

A solid circle crossed by diagonal lines indicates that the specimen after previous test at lower stress was subjected to the indicated stress and number of cycles and the stress was then increased.

A solid circle crossed by a vertical and horizontal line indicates that the specimen after previous test at lower stress was subjected to the indicated stress and number of cycles and the specimen was then removed.

Whenever the stress was increased during an endurance test of any specimen the number of cycles at the increased stress was plotted with zero as origin.

The entire record of the endurance test on the first specimen of a set is given in order to show whether or not there is any apparent strengthening effect of thus starting at a stress considerably below the endurance limit and increasing the stress repeatedly by small increments.

No attempt has been made to draw idealized lines to represent the stress-cycle relationships for the various kinds of steel. The points representing results of experiments are too few to make such idealized lines possible even if they were desirable. Results of many experiments described in previous papers(1,2,4) have shown that for steels the stress-idealized cycle graph as plotted semi-logarithmicly is a curve whose radius of curvature increases and whose downward slope decreases with decrease of stress until the graph becomes practically a straight line with downward slope so slight that it is doubtful whether or not the line is actually horizontal. For this reason short horizontal lines have been drawn at the estimated points where the idealized graphs would cut the ordinates corresponding to 10,000,000 cycles.

Since in the graphs, shown in Figs. 9 to 14, inclusive, the points representing experimental results are few, the positions of some of these short horizontal lines cannot be located as accurately as is

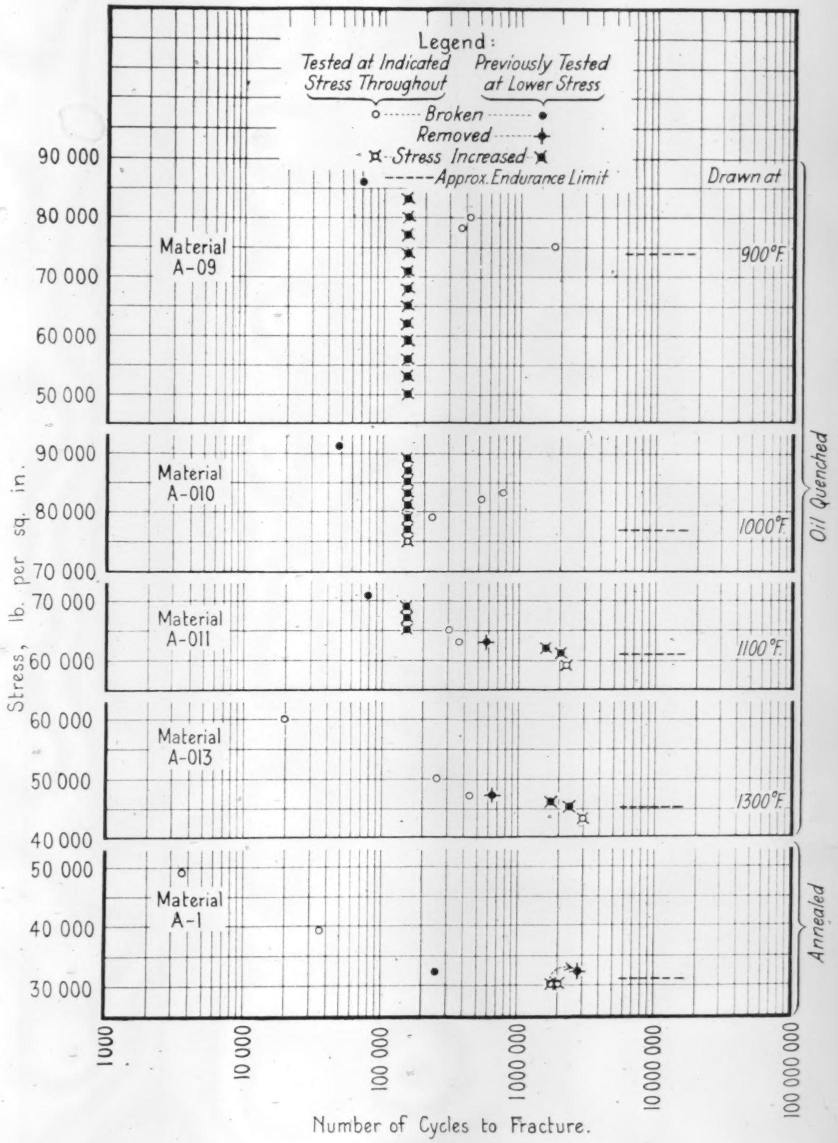

FIG. 9.—Results of Rotating Cantilever Endurance Tests, Material A.

desirable. Nevertheless, when account is taken of the slight strengthening effect of testing specimens under repeatedly increased stress and when the general shape of an idealized stress-cycle graph is also considered, it is believed that none of the lines representing endurance limits is in error by more than 1000 or 2000 lb. per sq. in.

Description of Figs. 9 to 14, inclusive.—Fig. 9 shows results of endurance tests of "Stainless Iron," material A. The endurance limit of material A-010 that had been drawn at 1000° F. is slightly higher than that of material A-09 that had been drawn at 900° F. The endurance limit decreases rapidly, however, with increase of drawing temperature above 1000° F. The endurance limit of material A-013 that had been drawn at 1300° F. is little more than one-half the endurance limit of material A-010 that had been drawn at 1000° F.

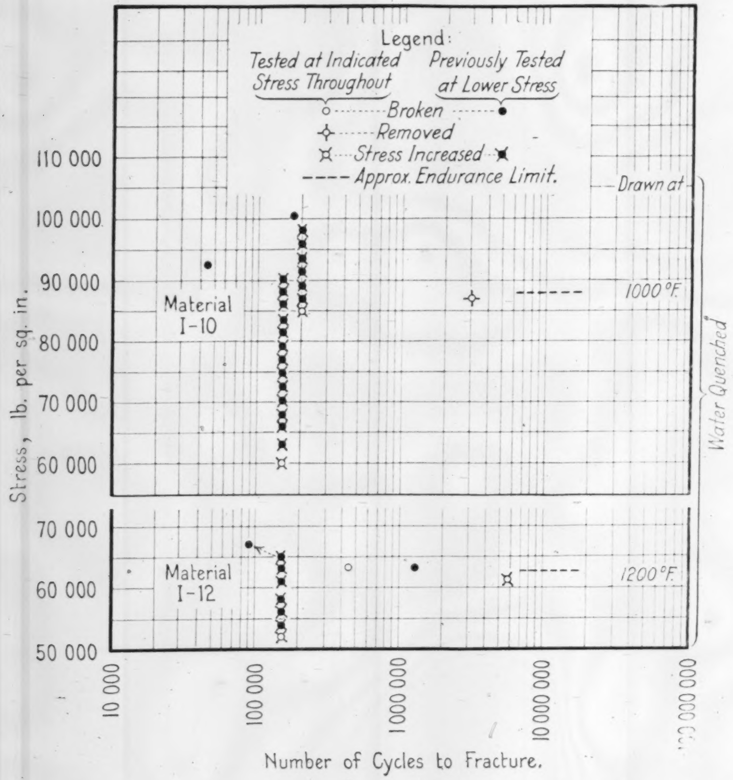

FIG. 10.—Results of Rotating Cantilever Endurance Test, Material I.

Fig. 10 shows results of endurance tests of material I. This material has about the same percentage of chromium as material A.

The endurance limits of material I are evidently higher for the same drawing temperature than the endurance limits of material A.

Fig. 11 shows results of endurance tests of material J. This material has a higher percentage of chromium than material I, but the percentage of carbon of these two steels is practically the same. As is shown in Fig. 10, the endurance limit of material I decreases rapidly with increase in drawing temperature from 1000 to 1200° F. As shown in Fig. 11, the endurance limit of material J decreases rapidly with

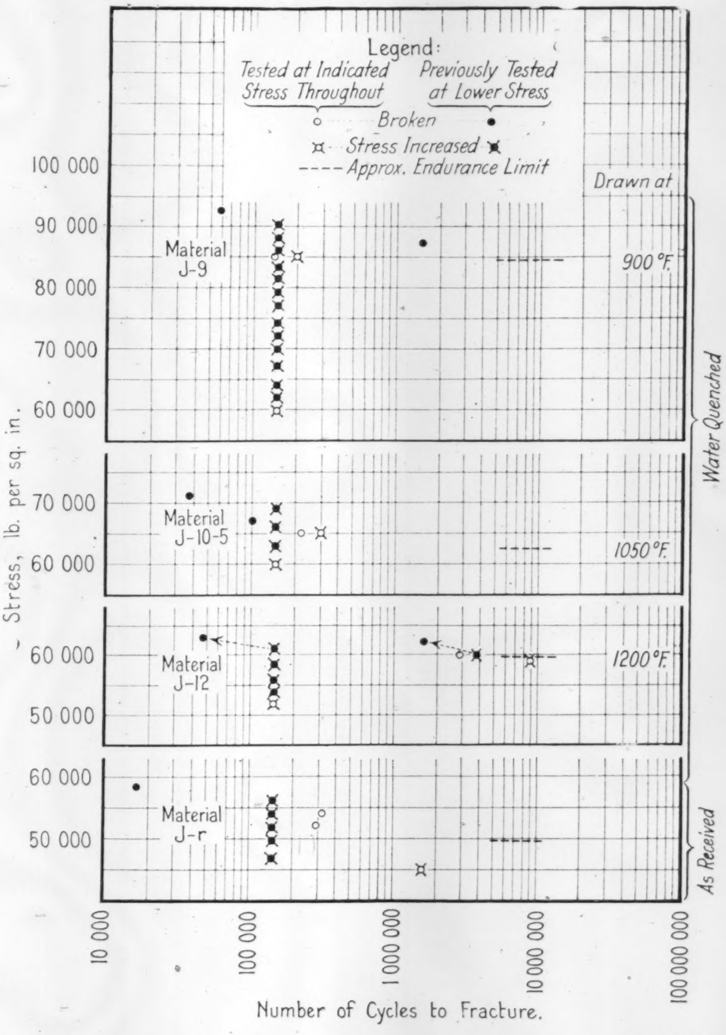

Fig. 11.—Results of Rotating Cantilever Endurance Test, Material J.

increase in drawing temperature from 900 to 1050° F. and decreases only slightly with increase in drawing temperature from 1050 to 1200° F. The endurance limit of the annealed material J(*r*) is still lower. It is of interest to note that the higher percentage of chromium of material J has not resulted in appreciably higher endurance limits.

Fig. 12 shows results obtained with material B. This material has about the same percentage of chromium as material J but its percentage of carbon is considerably higher. The endurance limit of the quenched material B-9 is considerably higher than that of the similarly quenched material J-9. The endurance limit of the annealed material B(*r*), however, is only slightly higher than that of the annealed material J(*r*).

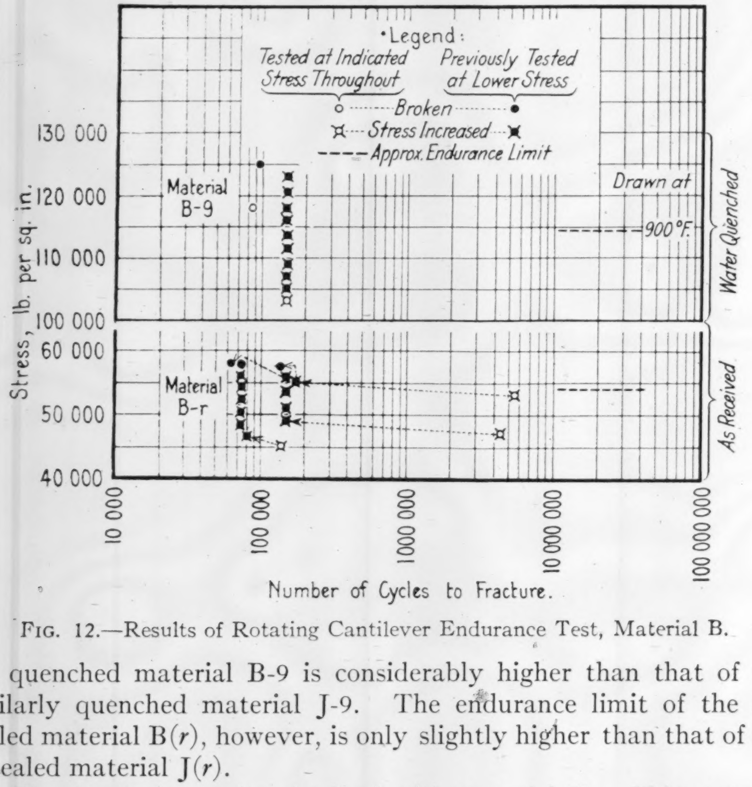

Fig. 12.—Results of Rotating Cantilever Endurance Test, Material B.

Fig. 13 shows results obtained with material K. This material has about the same percentage of chromium as materials J and B, but its percentage of carbon is considerably higher than that of material B and more than twice as high as that of material J. The endurance limit of quenched material K-9 is slightly lower than that of similarly quenched material B-9 but considerably higher than that of quenched material J-9. The endurance limit of quenched material K-10.5 is nearly 50 per cent greater than that of similarly quenched material J-10.5. With higher drawing temperature, the difference

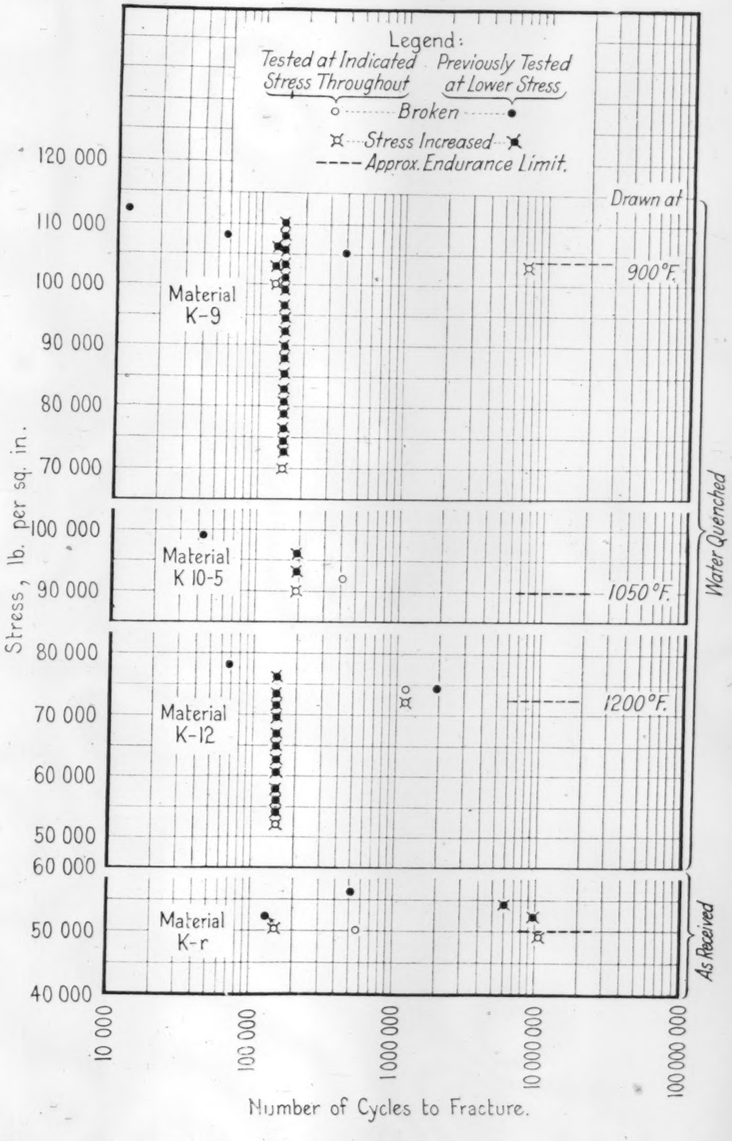

FIG. 13.—Results of Rotating Cantilever Endurance Test, Material K.

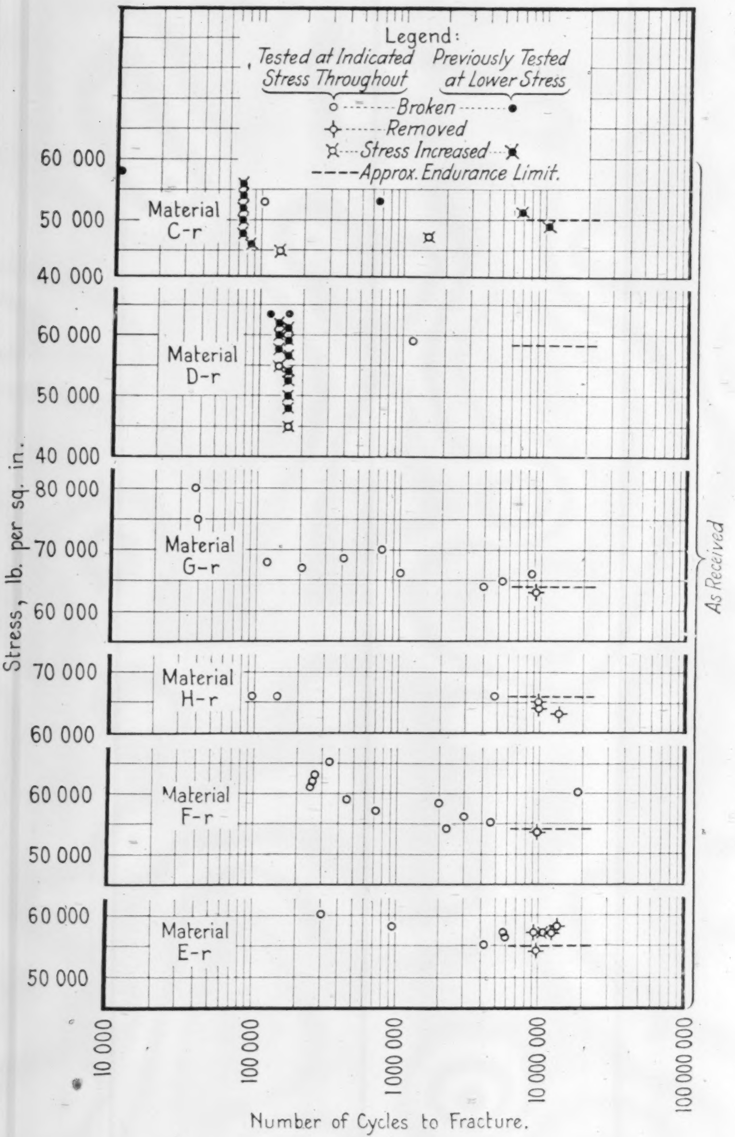

FIG. 14.—Results of Rotating Cantilever Endurance Test, Materials C, D, G, H, F and E.

between the endurance limits of the two kinds of material becomes less. In the annealed condition, the endurance limits of the two kinds of material are equal.

Fig. 14 shows results obtained with the various kinds of high-nickel, high-chromium steels. These steels, which had been annealed by the manufacturers, were tested as received. It will be noted that in spite of the great differences in composition of these steels, the differences in endurance limit in the annealed condition are relatively slight. The endurance limits of materials C(*r*), D(*r*), F(*r*), and E(*r*) are practically the same as the endurance limits of the annealed stainless steels, materials J(*r*), B(*r*), and K(*r*). The endurance limits of materials G(*r*) and H(*r*) are slightly higher. Whether or not this is due to the lower nickel content of these two steels could only be decided after comparative tests on material from other heats of steel.

ALTERNATING-TORSION ENDURANCE TESTS

General Description of Tests.—For investigating the endurance properties of metals by means of the alternating-torsion machine of the inertia type, three methods are available, the "fatigue method," the "deflection method," and the "accelerated fatigue method."

The method used until recently may be called the "fatigue method." The test specimen used in an endurance test by this method was so short that it was not considered necessary to take account of the increase in amplitude of oscillation of flywheel due to increasing twist of the specimen as it gradually failed. Although during the gradual weakening of a specimen under test the amplitude of oscillation of the flywheel, and hence the stress in the specimen, tends to increase slightly, it was assumed that throughout the test the range of torque remained constant as does the bending moment throughout an endurance test by the rotating cantilever method.

In an alternating-torsion test with the inertia machine, the amplitude of oscillation of the flywheel depends not only on the radius of crank-pin motion but on the twist of the specimen. The amount of the twist is readily determined by subtracting the amplitude of oscillation due to crank-pin motion from the total amplitude of oscillation. These values may be readily measured by means of the optical lever system(3) used in this machine. Stress-deflection graphs may, therefore, be obtained by gradually increasing the speed of the machine and taking readings at regular intervals. It was considered desirable to use such stress-deflection graphs as a possible means of obtaining endurance limits by the "deflection method" described by Gough(5). For this purpose the "R type" specimen shown in Fig. 2 was used. This specimen had been previously adopted for the purpose of obtaining endurance limits by the "accelerated fatigue method" described below.

In obtaining endurance limits by the deflection method, stress-deflection graphs are plotted and an attempt is made to determine the stress above which the graph ceases to be a straight line. Above this point, which can be determined with more or less accuracy, increase of deflection is no longer proportional to increase of stress. The determination of this point is analagous to the determination of the proportional limit in a tension test and is surrounded with the same difficulties.

In absence of experimental data there would be no reason to assume that in a specimen subjected to alternating torsion this limit of proportionality of deflection to stress corresponds to an endurance limit. Gough(5), however, determined experimentally in the case of some steels that this limit of proportionality corresponds rather closely to the "endurance limit." Investigation of the method at the Naval Experiment Station has shown that it is not applicable to non-ferrous metals and does not give accurate results with all kinds of steel.

For the "accelerated fatigue" method(6) it is necessary to use a long specimen so that the amplitude of oscillation due to twist is a large proportion of the total amplitude of oscillation. For this reason the "R type" specimen shown in Fig. 2 was used in investigating the corrosion-resistant steels. When such a specimen weakens under repetition of stress, the angle of twist of the specimen, and hence the total amplitude of oscillation of the flywheel, increases. The nominal stress, therefore, increases during the gradual yielding of the specimen and accelerates the failure.

It should be pointed out that the accelerated fatigue method does not depend on determination of a limit of proportionality of deflection to stress as does the deflection method. The accelerated fatigue method consists in determination of the stress above which the deflection, and hence the stress, increases automatically until the specimen breaks. This automatically accelerated increase of stress causes the specimen to fail after much fewer cycles of stress than if the nominal stress were constant as in the ordinary fatigue test. For this reason it may be called the accelerated fatigue method.

The specimens used for alternating-torsion tests of corrosion-resistant steels were taken from the ends by which the rotating cantilever specimens had been held in the machines during the rotating cantilever tests. For this purpose the rotating cantilever specimens that were to be used had been made somewhat longer than the

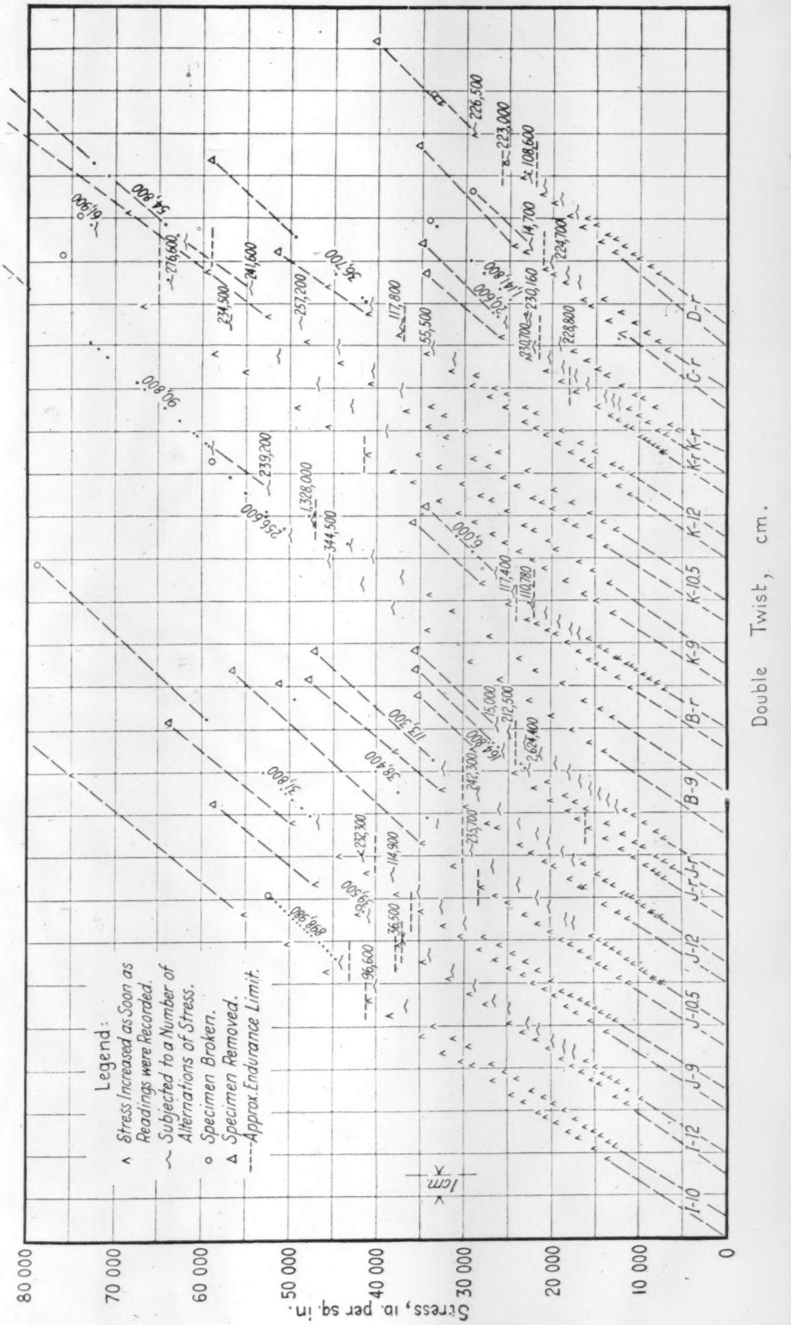

Fig. 15.—Results of Alternating-Torsion Tests.

dimension indicated in Fig. 1. Since only two or three alternating-torsion specimens of each material were available, the first test was usually made by the deflection method to determine, if possible, the approximate endurance limit. The second test was made by the accelerated fatigue method. In some cases a third specimen was available for an additional determination by the accelerated fatigue method. From the data thus obtained an estimate was made of the probable endurance limit for 10,000,000 cycles.

Description of Fig. 15.—The results of investigation of alternating-torsion endurance properties of corrosion-resistant steels are illustrated in Fig. 15. In this figure, stress-deflection graphs are used to illustrate results obtained by both the deflection method and the accelerated fatigue method. The curves representing the various kinds of steel are presented in the same order that was used in tables and graphs previously described. No curves for materials A, G, H, F and E are included since no alternating-torsion tests were made on these steels.

In Fig. 15, two or more curves are recorded to represent every composition and heat treatment. The first curve representing every material, except B-9, was obtained by the deflection method. All the other graphs were obtained by the accelerated fatigue method. The various points on the stress-deflection curves are represented by five kinds of marks.

A sharp-pointed arrow tip indicates that the stress was increased to this point, usually by increasing the frequency of oscillation of the flywheel. At this point the frequency was held constant only long enough to permit accurate observation of the amplitude of oscillation so that stress and deflection could be calculated. The stress was then increased and another reading taken to obtain a higher point on the graph.

A blunt-pointed arrow tip indicates that the stress was raised to this point and the specimen was then subjected to a number of cycles of stress. The number opposite such a mark indicates the number of cycles to which the specimen was subjected.

A dot in the graph indicates that the stress and deflection increased automatically to this point during an accelerated fatigue test. Sometimes, further increase in stress beyond this point occurred automatically, until the specimen failed. In this case the total number of cycles throughout the gradual automatic increase of stress is indicated by a number placed parallel to the graph.

Two kinds of marks are used to indicate the upper limit of a graph. A circle indicates that the specimen broke. A triangle indicates that the specimen weakened so that it was useless to continue the test further. In some cases, lack of space prevents the continuation of the graph to the upper limit made possible by stress-deflection measurements.

By means of the graphs obtained by the deflection method an attempt was made to determine the stress below which the deflection was proportional to the stress and above which the deflection increased more rapidly than the stress. This limit of proportionality, however, cannot be determined definitely in most of the graphs representing results obtained by the deflection method. Some of the graphs are apparently curved from the origin. In these no limit of proportionality has been indicated. In other graphs the curvature below the point that has been selected as the limit of proportionality is so slight that this part of the graph may be assumed to be straight. The limits of proportionality thus obtained have been marked P. L. on the graphs. The limit of proportionality of stress to deflection is evidently not much more definite in alternating torsion than in the tension test graphs of these corrosion-resistant steels. The endurance limits of these steels, therefore, cannot be accurately determined by the deflection method alone.

Examination of the graphs obtained by the accelerated fatigue method makes it apparent that, when the stress is gradually increased to the point at which further increase of stress and deflection occurs automatically, there is at this point a definite change of direction of the curve. This change of direction is much more abrupt than any curvature at the corresponding point of a graph obtained by the deflection method. In deciding whether or not this point of automatic increase of stress and deflection is an approximate endurance limit it is necessary to take into account the number of cycles during which this automatic increase occurs. If from the beginning of automatic increase to the failure of the specimen the number of cycles is small, it is probable that a point of slower automatic increase could have been found at a lower stress. This point at which slow automatic increase of stress begins and proceeds until the specimen fails may be designated as the endurance limit.

As shown in the fatigue test graph of material I-10, for example, when the stress was raised to about 44,000 lb. per sq. in., a slow automatic increase of stress and deflection began and continued until the specimen broke at about 52,400 lb. per sq. in. stress. The increase in stress from 44,000 to 52,400 lb. per sq. in. required about 900,000 cycles. Since a steel specimen that has endured a constant nominal range of stress for 900,000 cycles has been stressed not far above its endurance limit, it is evident that a specimen that has endured automatically increasing nominal stress for 900,000 cycles has been, at the beginning of this period, stressed only slightly above its endurance limit. For this reason the endurance limit of material I-10 has been marked on the graph at about 43,000 lb. per sq. in. By making use of these principles and with the aid of stress-cycle graphs not here shown, the endurance limits of all the corrosion-resistant steels that were tested under alternating torsion have been determined and indicated in Fig. 15.

A comparison of the endurance limits obtained by the accelerated fatigue method with the indefinite proportional limits obtained by the deflection method shows that the agreement in general is not good. The proportional limits obtained by the deflection method are usually lower, sometimes much lower, than the endurance limits obtained by the accelerated fatigue method. In a few cases the endurance limit is slightly below the proportional limit. The deflection method evidently does not give accurate determination of the endurance limits of corrosion-resistant steels. The proportional limits obtained by the deflection method, therefore, have been disregarded in deciding on the endurance limits of these steels.

RELATIONSHIP OF ROTATING CANTILEVER ENDURANCE LIMITS TO SOME TENSILE PROPERTIES

Relationship of endurance limits to some tensile properties are illustrated by Figs. 3 to 8, inclusive. In all these graphs on which a rotating cantilever endurance limit is recorded this limit is above the recorded proportional limit. In all but one of the graphs, the rotating cantilever endurance limit equals or exceeds the recorded elastic limit. In a large proportion of the graphs, the rotating cantilever endurance limit either exceeds or practically equals Johnson's limit. In some of the graphs this endurance limit is above what would ordinarily be called the yield point. It is evident, therefore, that the relationship of rotating cantilever endurance limit to proportional limit, elastic limit or Johnson's limit is extremely irregular. The metal at this endurance limit has usually received considerable cold working.

ENDURANCE RATIOS

Investigations of the endurance properties of a great variety of steels(1,2,7,8,9) have given considerable information in regard to the ratios of rotating cantilever endurance limit to tensile strength. This ratio is now in general use as a measure of the suitability of various kinds of steel for use in machinery parts subject to a repeated range of stress. In a previous paper(2) this ratio was called the "endurance ratio" on account of its analogy to the "elastic ratio." Recent investigations(2,7) of alternating-torsion endurance properties, however, have given much information in regard to alternating-torsion endurance limits of steel and have made it possible to calculate ratios of alternating-torsion endurance limit to tensile and to torsional strength. Other recent investigations(10) seem to indicate that the tension-compression endurance limit of steel is considerably lower than the rotating cantilever endurance limit. If these conclusions are confirmed, the ratio of the tension-compression endurance limit to the tensile strength will be another important index of the endurance properties of the various kinds of steel. Four ratios of endurance limit to static tensile and torsion properties of steel may, therefore, be called "endurance ratios."

The ratios of alternating-torsion endurance limit to rotating cantilever endurance limit and to tension-compression endurance limit are other important ratios. The former ratio differs greatly for various kinds of steel. It probably depends on the mechanical treatment of the steel and on other influences that produce what Henry M. Howe(11) called "fiber." The ratio of tension-compression endurance limit to rotating cantilever endurance limit may also be found to be of considerable importance. These ratios between the various endurance limits of the same piece of steel would naturally be called "endurance ratios." It seems advisable, therefore, not to restrict the term "endurance ratio" to the ratio of rotating cantilever endurance limit to tensile strength but to use it as a generic term to indicate any of the above-mentioned ratios.

It is important that terms be adopted to designate the various kinds of endurance ratio. Such terms are necessary to facilitate comparison and discussion of these important ratios. It would seem desirable that this subject be considered by the A.S.T.M. Committee on Nomenclature. For present use, however, the nomenclature described below has been adopted.

Ratio of an endurance limit to a static tensile or torsion property has been designated "static endurance ratio." Ratio of one kind of endurance limit to another has been designated "endurance ratio." To either of these generic terms two appropriate words must be prefixed to designate any specific endurance ratio. For brevity the specific term "bend" is used to designate rotating cantilever (or rotating beam) endurance limit, and "torsion" is used to designate alternating-torsion endurance limit. The nomenclature will be made clear as it is used.

In Table V are assembled all the values obtained for tensile strength, torsional strength, and endurance limits. From these values the various endurance ratios have been calculated. They are recorded in columns 9 to 12, inclusive, of Table V.

Bend-Tension Static Endurance Ratio.—The calculated value for the bend-tension static endurance ratio for each of these corrosion-resistant steels has been recorded in column 10 of Table V. As shown in this column the ratio varies from 0.444 to 0.573. The average of all the individual ratios is 0.511 and the average departure from this average is 0.031. It may be of some significance that the lowest ratios were obtained with annealed steels J(*r*), K(*r*) and F(*r*), and with materials A-09 and K-9 that had been drawn at 900° F. In annealed steels B(*r*), C(*r*), D(*r*), H(*r*) and E(*r*), however, the ratio is not low. The accuracy of the determination of the endurance limit of some of these steels was probably not great enough to justify an

TABLE V.—RATIO OF ENDURANCE LIMITS FOR TEN MILLION CYCLES TO TENSILE STRENGTH AND TORSIONAL STRENGTH.

Material Designation	Cooled in	Drawn at — deg. Fahr.	Average Tensile Strength, lb. per sq. in.	Average Torsional Strength, lb. per sq. in.	Endurance Limits for 10,000,000 Cycles		Ratios				
					Rotating Cantilever	Alternating Torsion	Column 5 to Column 4	Column 7 to Column 6	Column 6 to Column 4	Column 7 to Column 4	Column 7 to Column 5
1	2	3	4	5	6	7	8	9	10	11	12
A-09	Oil	900	166 500	......	74 000	......	......	......	0.444	......	......
A-010	"	1000	164 600	......	77 000	......	......	......	0.468	......	......
A-011	"	1100	109 500	......	61 000	......	......	......	0.557	......	......
A-013	"	1300	83 250	......	45 000	......	......	......	0.541	......	......
A-1	Furnace	......	63 250	......	31 000	......	......	......	0.490	......	......
I-10	Water	1000	171 500	110 490	88 000	43 000	0.644	0.488	0.513	0.250	0.389
I-12	"	1200	121 500	83 320	62 500	37 000	0.686	0.592	0.514	0.305	0.444
J-9	Water	900	164 300	110 490	84 500	40 000	0.672	0.473	0.514	0.243	0.362
J-10.5	Water	1050	123 250	93 290	62 500	30 000	0.757	0.489	0.507	0.243	0.322
J-12	Water	1200	115 700	73 360	59 500	30 000	0.534	0.504	0.515	0.259	0.408
J(*r*)	As received		110 000	70 640	49 500	24 000	0.642	0.484	0.450	0.218	0.334
B-9	Water	900	199 500	118 650	114 500	47 000	0.594	0.410	0.573	0.235	0.396
B(*r*)	As received		99 750	76 080	54 500	22 000	0.762	0.403	0.546	0.221	0.289
K-9	Water	900	230 300	150 350	104 000	65 000	0.653	0.625	0.452	0.282	0.432
K-10.5	"	1050	167 640	129 970	90 000	59 000	0.775	0.655	0.537	0.351	0.453
K-12	"	1200	131 500	87 170	72 500	37 000	0.662	0.513	0.551	0.281	0.424
K(*r*)	As received		111 000	84 230	50 000	21 500	0.759	0.430	0.450	0.194	0.255
C(*r*)	As received		96 000	69 290	50 000	21 000	0.721	0.420	0.521	0.219	0.303
D(*r*)	As received		111 100	72 810	58 500	22 000	0.655	0.376	0.526	0.198	0.302
G(*r*)	As received		130 000	84 680	64 000	......	0.651	......	0.492	......	......
H(*r*)	As received		123 000	......	65 500	......	......	......	0.532	......	......
F(*r*)	As received		118 250	74 270	54 000	......	0.628	......	0.457	......	......
E(*r*)	As received		106 500	81 060	55 500	......	0.761	......	0.521	......	......

assumption of accuracy of the endurance static ratio within less than ±0.02. For this reason too much stress should not be laid on the differences between the ratios given in column 10 of Table V. Nevertheless, since results of an investigation(2) of the bend-tension static endurance ratio of a number of carbon and alloy steels indicate that this ratio is higher in quenched-and-drawn than in annealed steels, it seems probable that for corrosion-resistant steels also the static endurance ratio is slightly higher in the quenched-and-drawn than in the annealed condition.

The average bend-tension static endurance ratio for corrosion-resistant steels is slightly higher than the averages of similar ratios for nickel, chrome-molybdenum, chrome-vanadium, and chrome-nickel steels as given in Table XI of a previous paper(2). For corrosion-resistant steels, therefore, this ratio is practically the same as for other alloy steels that have been investigated.

Torsion-Tension Static Endurance Ratio.—The ratios of alternating-torsion endurance limit to tensile strength are given in column 11 of Table V. The ratios vary from 0.194 to 0.351. They vary much more than do the ratios given in column 10. Without exception the annealed steels gave the lowest ratios. For the five annealed steels, for which this ratio was determined, it varies from 0.194 to 0.221 and the average is 0.210. The quenched-and-drawn steels gave the the following average values:

Material I	0.277
Material J	0.248
Material B	0.235
Material K	0.305

Evidently, therefore, the torsion-tension static endurance ratio is higher for the quenched-and-drawn than for the annealed steels. In a previous investigation 2) a similar superiority of quenched-and-drawn over annealed material was found for other alloy steels.

The range of ratios for corrosion-resistant steels is evidently about the same as that for other alloy steels. The range of ratios for carbon and alloy steels as given in Table XI of the previous paper(2) is exactly the same as the range of ratios in column 11 of Table V. The alternating-torsion endurance properties, as well as the rotating cantilever endurance properties of the corrosion-resistant steels, therefore, are similar to those of other alloy steels that have been investigated.

Torsion-Torsion Static Endurance Ratio.—The ratios of alternating torsion endurance limit to torsional strength are given in column 12 of Table V. The range of individual ratios is from 0.255 to 0.453. This range is proportionally about the same as the range of ratios in column 11. The lowest ratios are those of annealed steels. The range of ratios for annealed steels is from 0.255 to 0.334, whereas the range of ratios for quenched-and-drawn steels is from 0.322 to 0.453. The average ratio for annealed steels is 0.297, whereas the average ratio for quenched-and-drawn steels is 0.403. In a previous investigation(2) a similar superiority of quenched-and-drawn over annealed material was found for other alloy steels. The torsion-torsion static endurance ratios for corrosion-resistant steels are within the range of ratios previously found for other alloy steels(2).

Torsion-Bend Endurance Ratio.—The ratios of alternating-torsion endurance limit to rotating cantilever endurance limit are given in column 9 of Table V. The range of individual ratios is from 0.376 to 0.655, whereas in Table XI of a previous paper(2) the range of individual ratios for carbon and nickel steels is from 0.441 to 0.807 and the range of average ratios is from 0.549 to 0.684. For corrosion-resistant steels, as for carbon and nickel steels, annealed material apparently gives lower torsion-bend endurance ratios than does quenched-and-drawn material.

It seems probable that the torsion-bend endurance ratio depends largely on the mechanical treatment to which the bar or forging has been subjected. The rotating bend endurance limit depends on the strength of the metal in a longitudinal direction. The alternating-torsion endurance limit, however, depends on the strength of the metal in a transverse as well as in a longitudinal direction. In some steels this endurance limit evidently depends chiefly on the resistance of the metal to both longitudinal and tranverse shear; such steels fail by longitudinal cracks and transverse fracture. In other steels the alternating-torsion endurance limit apparently depends on the resistance of the metal to tensile and compressive stress in a direction making an angle of 45 deg. with the longitudinal axis; such steels fail by helical fracture. Whether the metal fails by longitudinal and transverse shear or by helical fracture, however, the alternating-torsion endurance limit depends on the physical properties of the metal in a transverse as well as in a longitudinal direction. The relationship between transverse and longitudinal properties depends on the mechanical treatment to which the bar or forging has been subjected and on other influences that produce "fiber."

The torsion-bend endurance ratio may, therefore, prove to be an important index of the effect of degree of reduction of cross-section in rolling or forging of machinery parts for purposes in which transverse as well as longitudinal properties are of importance. At the Naval Experiment Station an extensive investigation of this subject is now under way.

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References

(1) D. J. McAdam, Jr., "Endurance of Steel under Repeated Stresses," *Chemical and Metallurgical Engineering*, December 14, 1921.

(2) D. J. McAdam, Jr., "Endurance Properties of Steel: Their Relation to Other Physical Properties and to Chemical Composition," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 56 (1923).

(3) D. J. McAdam, Jr., "A High-Speed Alternating Torsion Testing Machine," *Proceedings*, Am. Soc. Testing Mats., Vol. XX, Part II, p. 366 (1920).

(4) D. J. McAdam, Jr., Discussion of paper by Moore, Kommers, and Jasper on "Fatigue of Metals," *Proceedings*, Am. Soc. Testing Mats., Vol. 22, Part II, p. 288 (1922).

(5) H. J. Gough, "Improvements in Methods of Fatigue Testing," *The Engineer*, August 12, 1921.

(6) D. J. McAdam, Jr., "Accelerated Fatigue Tests and Some Endurance Properties of Metals," *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part II, p. 454 (1924).

(7) H. F. Moore and J. B. Kommers, "An Investigation of the Fatigue of Metals," *Bulletin No. 124*, University of Illinois, Vol. 19, No. 8, October 24, 1921.

(8) H. F. Moore, J. B. Kommers and T. M. Jasper, "Fatigue or Progressive Failure of Metals under Repeated Stress," *Proceedings*, Am. Soc. Testing Mats., Vol. 22, Part II, p. 266 (1922).

(9) H. F. Moore and T. M. Jasper, "An Investigation of the Fatigue of Metals," *Bulletin No. 136*, University of Illinois, Vol. 20, No. 37, May 14, 1923.

(10) H. F. Moore and T. M. Jasper, "An Investigation of the Fatigue of Metals," *Bulletin No. 142*, University of Illinois, Vol. 21, No. 39, May 26, 1924.

(11) H. M. Howe, "The Metallography of Steel and Cast Iron," pp. 546–592.

THE CARRYING CAPACITY OF BALL BEARINGS MADE OF STAINLESS STEEL

By Axel Hultgren[1]

As is well known, balls and rings of ordinary ball bearings are made of chromium steel of the approximate composition, carbon 1.0 per cent, chromium 1.5 per cent, and hardened to full hardness, that is, 650 to 700 Brinell. This material and heat treatment are chosen mainly for the following two reasons:

1. Great hardness is required in order that the high compressive stresses on the small contact surfaces between balls and race-ways may be resisted without permanent deformation.
2. High fatigue strength is necessary in order to endure the great number of alternating stresses, to which the surface portions of balls and race-ways are subjected during the running of the bearing. Any material that is inferior in hardness or fatigue strength will therefore hardly be considered for ball bearings, except in very special cases, where the load transmitted is small and low frictional resistance only is demanded.

Chromium steel of the composition given does not differ from ordinary carbon steel in regard to its tendency to rust when exposed to direct action of moisture or other corroding agencies. Partly on this account the ball bearing is commonly mounted in a housing, enclosing it as tightly as possible. In the space between the rotating shaft and the surrounding part of the housing, some sealing device containing felt or the like is provided. By filling the housing in proper amount with soap grease, at the same time a suitable lubricant for ball bearings under ordinary conditions, an additional sealing effect is obtained. Such protection is essential to the permanence of the bearing. Rusting of balls and race-ways will increase the friction in the bearing, cause wear, and the small pits formed will provide nuclei, from which fatigue cracks may start and finally develop into so-called flaking. In cases where actual splashing of water occurs, more elaborate sealings built upon the labyrinth principle have been employed with success.

However, when severe corroding conditions are encountered, for instance, in machinery exposed to sea-water or continuously submerged in water, such devices and precautions are of no avail. Then the use of non-rusting metals for ball bearings has been resorted to. Until a few years ago high-hardness bronze was usually employed for this purpose. Although a Brinell hardness of 200 and more may be obtained in such material, it is rather soft as compared with hardened ball-bearing steel. This necessitated ample dimensioning of the bearings, and in consequence the use of bronze ball bearings has been rather limited.

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After Stainless steel was discovered and it became known that this steel, after being properly hardened, showed a Brinell hardness of up to 600, ball bearing manufacturers naturally turned their attention to this material, expecting to find the solution of the problem of rust-resisting ball bearings. Accordingly, during the past six years Stainless steel as a ball bearing material has been tested on different occasions in the Gothenburg Laboratory of Aktiebolaget Svenska Kullagerfabriken. A brief summary of these tests, the results of which are far from promising, will now be given.

The rust-resisting qualities of Stainless steel properly heat treated are fairly well established by numerous tests made by manufacturers and users of such steel. Tests of this kind were also made, but need not be dealt with here. The main interest was concentrated on the carrying capacity or endurance of Stainless ball bearings, particularly under conditions that would obtain in service, where such bearings would be used.

In order to determine the carrying capacity of a ball bearing, the bearing—preferably eight, ten, or more bearings should be tested—is loaded with a certain over-load and allowed to run until failure occurs. For a certain type or design of ball bearing the carrying capacity is governed mainly by the number and size of balls and, of course, by the properties of the material. The load that can be carried by a ball is roughly proportional to the square of its diameter. In order to be able to deal with different sizes on a common basis it is therefore convenient to speak of the specific load[1] on a ball, that is,

$$k = \frac{p}{d^2}$$

where $p =$ load on the ball in kilograms (or pounds) and $d =$ diameter in eighths of an inch. In a radial ball bearing, that is, a bearing that takes load in a direction at right angles to the shaft, the specific load is

$$k = \frac{5P}{nd^2}$$

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[1] Stribeck: *Zeitschrift des Verein deutscher Ingenieure*, p. 73, 1901.

where P = total load on the bearing and n = number of balls. In that case k signifies the specific load for the highest loaded ball.

In all tests to be described, the bearings were of the self-aligning type with spherical outer race-way and two rows of balls. A common test load for such bearings is $k = 20$ kg. When run at a speed of 1000 r. p. m. the majority of such bearings of ordinary chromium steel will show an endurance exceeding 100 hours, that is, 6,000,000 revolutions, before failure occurs. For comparison, a normal service load for such bearings may be given as $k = 5$ kg.

The actual procedure of testing was as follows: A number of bearings were made, the rings and balls being made of Stainless steel, the retainers pressed from brass sheet. The bearings were mounted in a testing machine and were allowed to run under a load that was regulated as closely as possible to give an endurance comparable to that obtained with ordinary ball bearings under a load of $k = 20$ kg. Tests were run partly without water being allowed to come in contact with the bearing and partly with dripping water passing continuously through the bearing during running. Obviously the results of the latter tests will be more representative of the behavior of the bearings in service. The speed adopted was invariably 1000 r. p. m. As lubricants, petroleum grease and soap grease were tried. It was found that petroleum grease was soon washed away by the stream of water, whereas the soap grease remained in the bearing. In one case it was found after the test that the water content of the remaining soap grease had increased to 8 per cent.

TABLE I.—TESTS OF AMERICAN STAINLESS STEEL BALL BEARINGS.

Speed = 1000 r. p. m.

Bearing No.	Specific Load, kg.	Lubricant	Water	Endurance, hours	Remarks
1	10	soap grease	absent	62	2 balls flaked.
2	10	"	"	36	1 ball flaked.
3	10	"	"	43	1 ball flaked.
4	5	none	present	27	Outer ring and 5 balls flaked.
5	2	"	"	36	1 ball flaked.
6	5	petroleum grease	"	21	Outer race flaked.
7	5	"	"	12	11 balls flaked.
8	5	"	"	23	Outer race flaked.
9	5	"	"	27	Outer race flaked.
10	5	soap grease	"	221	Outer race flaked.
11	5	"	"	150	Outer race and 1 ball flaked.
12	5	"	"	56	Outer race and 1 ball flaked.
13	5	"	"	79	Outer race and 3 balls flaked.
14	5	"	"	134	Outer race and 2 balls flaked.

NOTE.—No rusting was observed.

Three test series were run with bearings made of Stainless steels from an American, a British and a Swedish source, respectively.

AMERICAN STAINLESS STEEL

The composition of the steel as given by the maker was: carbon 0.50 to 0.60, chromium 12 to 14, manganese 0.30, silicon 2, phosphorus 0.015, and sulfur 0.015 per cent. The high silicon and the somewhat high carbon content distinguish this steel from the ordinary type of Stainless steel.

Test bearings were of type SKF 1308 containing thirty $\frac{7}{16}$-in. balls and having the following dimensions:

Outside diameter	90 mm.
Bore diameter	40 "
Width	23 "

$k = 1$ kg. corresponds to a total load $= 73.5$ kg.

Rings and balls were hardened in oil from 1000° C. and tempered to 250° C. Test results are given in Table I.

TABLE II.—TESTS OF BRITISH STAINLESS STEEL BALL BEARINGS.

Speed = 1000 r. p. m. Lubricated with soap grease.

Bearing No.	Specific Load, kg.	Retainer	Water	Endurance, hours	Remarks
1	4	no retainer	present	12	Outer race flaked. Inner race worn.
2	2	"	"	29	Outer race flaked and worn. Inner race worn. Balls rough, "smeared."
3	2	"	"	21	Like previous one.
4	2	with retainer	absent	57	No failure. Balls somewhat dull. Test continued.
	2	no retainer	"	60	Outer race flaked and worn. Inner race worn. Balls rough, smeared.
5	2	with retainer	present	28	Outer race flaked. No wear.
6	2	"	absent	213	Outer race beginning to flake; outer race was turned 180 deg. and test continued.
	2	"	present	93	Outer race flaked.

NOTE.—No rusting was observed.

From these tests it may be inferred that in the absence of water these bearings are considerably inferior to ordinary ball bearings in regard to carrying capacity, the ratio being perhaps little more than 20 per cent; and that with water present the carrying capacity was further reduced to somewhat less than 20 per cent of that of ordinary bearings.

BRITISH STAINLESS STEEL

The composition of the steel was carbon 0.35 per cent, chromium 12.2 per cent. Manganese, silicon, phosphorus, and sulfur were not determined. Test bearings were SKF 1308 as in the previous series. Rings and balls were hardened in oil from 950° C. and tempered to 250° C. A Brinell hardness (5 mm., 750 kg.) of 476 to 499 was obtained in the rings after this treatment. In all tests the bearings were lubricated with soap grease. In order to determine whether a retainer was necessary or not, some bearings were run without the retainer. Results are given in Table II.

From these tests the following conclusions may be derived: The retainer is indispensable; if it is omitted, so-called "smearing" develops on the balls due to the rubbing of adjacent balls against each other, and in consequence the rings wear out rapidly. In the absence of water, the carrying capacity of these bearings was about 10 to 20 per cent, and in the presence of water, below 10 per cent of that of ordinary ball bearings.

SWEDISH STAINLESS STEEL

The steel had the following composition: carbon 0.30, chromium 15.45, nickel 0.20, manganese 1.00, and silicon 0.34 per cent. Test bearings were SKF 1306, containing twenty-six $\frac{3}{8}$-in. balls and having the following dimensions:

TABLE III.—TESTS OF SWEDISH STAINLESS STEEL BALL BEARINGS.

Speed = 1000 r. p. m. Lubricated with soap grease. Water kept flowing through bearing.

Bearing No.	Specific Load, kg.	Endurance, hours	Remarks
5	2	71	Outer race flaked.
4	2	100	No failure.
	5	22	Outer race flaked.
2	5	35	Outer race flaked.
8	2	100	No failure.
	5	39	Outer race flaked.
7	5	42	Inner race flaked.
6	2	100	No failure.
	5	56	Outer race flaked.
10	2	100	No failure.
	5	59	Outer race flaked.
9	2	100	No failure.
	5	68	Outer race flaked.
1	5	81	Outer race flaked.
3	2	100	No failure.
	5	92	Outer race flaked.

NOTE.—No rusting was observed.

Outer diameter	72 mm.
Bore diameter	30 "
Width	19 "

For this type of bearing, a specific load $k = 1$ kg. corresponds to 47 kg. total load on the bearing.

Rings and balls were hardened in oil from 1050° C. and tempered to 200° C. The Brinell hardness (5 mm., 750 kg.) obtained varied between 550 and 603.

All bearings were lubricated with soap grease, and water was kept flowing through the bearing as previously described. In some cases, when the bearing had run at $k = 2$ kg. for 100 hours, the load was increased to 5 kg. and the test continued. The results are given in Table III, arranged according to increasing endurance values.

The carrying capacity of these bearings may be estimated to be 10 to 20 per cent of that of ordinary bearings.

Ball bearings made of bronze in previous tests were found to have a carrying capacity below 10 per cent—probably about 5 per cent—of that of ordinary ball bearings.

CONCLUSION

In conclusion, it may be stated briefly that ball bearings made of Stainless steel, at least of the type tested, as regards carrying capacity seem to be very much inferior to ball bearings made of ordinary material and only slightly superior to such bearings made of bronze.

With such results at hand, it is not likely that Stainless steel will be used for ball bearings to any great extent. Perhaps properly designed roller bearings of Stainless steel will have sufficient carrying capacity to justify their use in cases where non-rusting material is necessary and the load is not too heavy. This remains to be tested in the future.

SOME PRINCIPLES UNDERLYING THE SUCCESSFUL USE OF METALS AT HIGH TEMPERATURES

By F. A. Fahrenwald[1]

Introduction

The suitability of metals and alloys for high-temperature service depends primarily upon:

1. Physical Strength;
2. Chemical Resistivity.

To build these essential properties into satisfactorily operating equipment for carrying loads and into mechanisms or containers for the conduct of processes under conditions which maintain in all but the most simple of industrial high-temperature requirements is, however, far more difficult than in structural or mechanical engineering of a similar nature at normal temperature.

The complexity of problems involved in high-temperature engineering as related to the design and operation of metallic units has not been fully appreciated, and as a result many processes requiring the use of such equipment have been only partly successful, or abandoned as impracticable. Both design and operation have until recently been too much of a "hit-and-miss" procedure in which most of the underlying principles have been entirely disregarded. The lack of sound engineering and operating practice, however, is not wholly without cause, as the earliest production of heat-resisting alloys, and the development of actual industrial needs for such materials are of comparatively recent date. Even if fundamental principles underlying design and operation were fully recognized, and complete data concerning properties of materials at high-temperatures were available, man's ability properly to build principles and data into successfully operating metallic high-temperature equipment can be derived in a large measure only through experience.

During the past four or five years, however, production and engineering activities in many portions of the field have been based largely upon principles and data which, in general high-temperature application, have proved to be relatively as accurate for all practical purposes as those which govern similar activities at ordinary temperatures. By this is meant that, within the limits of more restricted possibilities at higher temperatures, heat-resisting alloy equipment can be manufactured with almost the same degree of advance assurance of successful service that obtains, for instance, in ordinary structural engineering.

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It is the aim of these notes to deal briefly and in a very general manner with some of the more important principles underlying the successful use of metals at high temperatures and to present therewith sufficient condensed data to either illustrate fundamentals or to indicate the nature of practical information available for use in this work. It is intended to discuss the subject as a whole from the general engineering and application point of view, and include a brief consideration of each of the more important variables involved, rather than to consider in detail any single phase of the field.

METALS FOR HIGH TEMPERATURES: PAST—PRESENT—FUTURE

Until about a decade ago non-metallic refractories and iron or steel were the only materials available for use at high-temperatures. Refractories cannot, of course, be utilized for mechanically operated or handled units so, in spite of a serious lack of both physical and chemical stability, enormous tonnages of steel were used and were largely destroyed through oxidation. Various ordinary steels form by far the larger portion of metallic materials employed for high temperature uses even to-day.

About twenty years ago it was learned that certain alloys possessed greater strength and resistance to oxidation at high temperatures than did ordinary steels, and the progressive development of this branch of metallurgy has made available the various so-called heat-resisting alloys of the present time. Through the use of alloys in which there has been developed to a high degree some especially desired property, it is possible to secure performance at high-temperature not obtainable in any pure metal nor in any refractory.

The expressions "high-temperature" and "heat-resisting" are relative only. The term "heat-resisting" as applied to alloys for use at high temperature is unfortunate in view of the diverse requirements of high-temperature industries and the impossibility of incorporating all kinds of resistivities in the same alloy. Heat-resisting alloys of the present time are so classed chiefly on the basis of their resistance to oxidation. Many of the more recent processes require alloy units to serve at high temperatures under reducing conditions or in contact with fused salts or corrosive gases of various kinds, and oxidation-resisting alloys are not necessarily resistant to these other environments. It is not possible to meet all high-temperature requirements with a corresponding degree of resistance in a given alloy but any one set of requirements can be met to a greater degree with a specially adapted alloy than through the use of any so-called all-purpose heat-resisting alloy.

In addition to the criteria of chemical resistivity, and physical strength, there are certain other properties and many outside factors by which the suitability of alloys for use at high temperatures must be judged. (Questions of production and cost are determining factors also but are purposely omitted here.)

Alloys available at the present time are of the solid solution type and all employ iron-group metals as a base with the addition of one or more other constituents to impart special characteristics.

In order to better understand the performance of available alloys and to indicate what may be expected from further developments it is necessary briefly to discuss those factors which cause certain alloys to be more stable chemically and physically than are their constituents.

Under the heading "Chemical Resistivity" (to be discussed) it is shown that chemical stability is due either to intrinsic inertness or to the protecting effect of a surface coating of the products of corrosion. Any metal possessing chemical inertness in itself will tend to ennoble another metal to which it is added and if in sufficiently high percentage it will, in general, impart to the alloy as a whole its own characteristic type of resistivity. The addition of nickel to iron, gold to copper, etc., are examples of this. Also, a metal which protects itself from progressive corrosion by means of a coating of a compound will tend to impart the same means of protection to the alloy of which it is a part. Thus, chromium is very easily oxidized but this corrosion is not progressive, due to the tenuous, impervious and highly refractory coating of oxide that is formed. Aluminum, zirconium and similar metals also possess this property but in a lesser degree. This type of immunity is imparted to alloys in which these metals are present in substantial amounts and this class includes nearly all of the "heat-resisting" alloys of the present time.

Unfortunately, metals are not available which are resistant to each of the many other forms of corrosive agencies encountered, so possibilities in the way of providing any required kind of "heat resistance" by either of these methods, are decidedly limited.

It has been found that with certain combinations of metals or of metals with metalloids or non-metals, definite chemical compounds result that do not in any of their properties resemble the original components. In this class are the corrosion-resisting iron-silicon alloys and the refractory silicon-carbide. All possibilities in this direction have not been exhausted and it is not unreasonable to expect the development of intermetallic compounds which will furnish a kind of chemical resistivity not possessed by any material available at the present time. As an example, resistance to oxidation at temperatures up to 3100° F. has been secured in materials of this class.

A discussion of physical strength (as well as chemical resistivity) should be accompanied by a consideration of the different types of alloy constituents and the properties and characteristic of each, in order to illustrate relationships between constitution (not necessarily composition) and properties, both physical and chemical, but space herein is not available and it is believed that this relationship is sufficiently well known to warrant the omission.

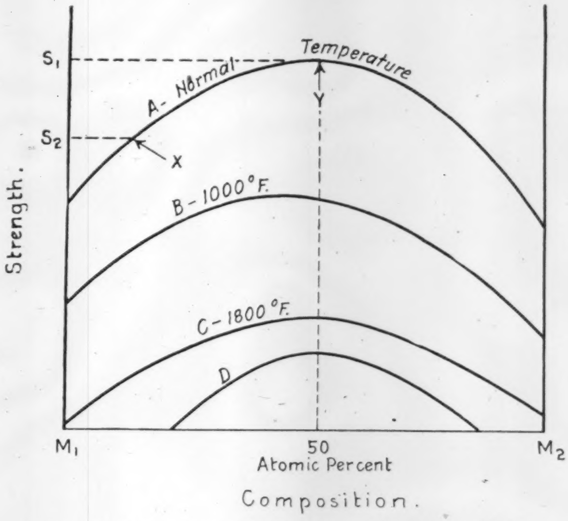

FIG. 1.—Variation of Strength with Composition.

In general, when one metal is alloyed with another, the strength and hardness are above that of the solute itself and this increase is progressive usually to 50 atomic per cent in the case of mutually soluble metals, and to the saturation point in the case of metals of limited solubility. (This refers only to cases of stable equilibrium and excludes all reference to saturation points or limits of dispersion which have been raised, with accompanying increase in strength, by heat treatment.) Most heat-resisting alloys at present available are of the solid solution type and most of these of the class that is completely soluble in all proportions. When iron or copper or any other soluble metal is added to nickel, for example, the resulting alloy is harder and stronger than nickel.

In Fig. 1, curve *A* represents the progressive increase in strength and hardness up to a certain (saturation) point. This curve is typical for solid solution alloys such as nickel-iron, nickel-chromium, nickel-copper and chromium-iron, although in some cases there is a variation from 50 atomic per cent for the maximum due to space lattice and crystal structure considerations.

Commercial alloys of the nickel-chromium and iron-chromium type which contain from 15 to 25 per cent of chromium correspond to point *x* on the curve with strength S_2 and so do not possess the maximum strength obtainable in these binary alloys. It is not commercially feasible, however, to employ the highest degree of physical strength which it is possible to impart to these alloys with only two components, because with the higher chromium content the cost of materials is greater and manufacture becomes more difficult, both in castings and in wrought forms. In the case of either alloy, as the 50 atomic per cent is approached, there is an increase in brittle hardness with an accompanying decrease in elongation and reduction of area. The alloys are more brittle at ordinary temperatures and become quite unmachineable. A tendency to segregation becomes more

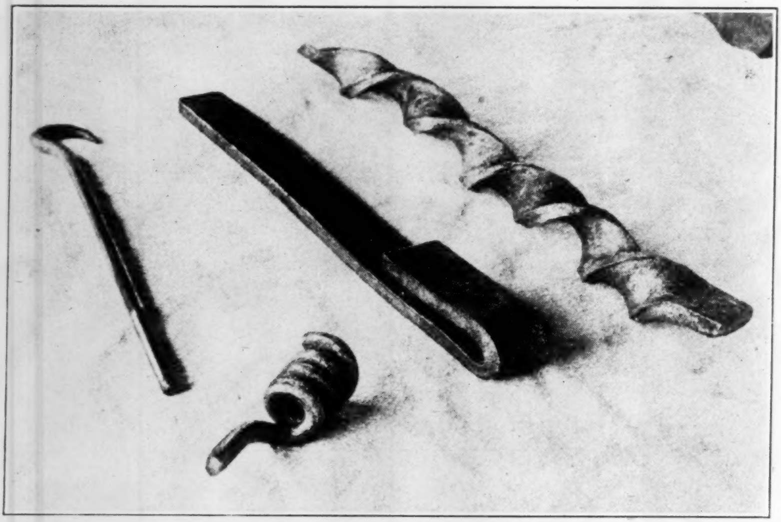

FIG. 2.—Examples of Low-Temperature Ductility of Fahrite N-1.

Flat bars, $\frac{3}{8}$ by $1\frac{1}{4}$ in. in section.
Rounds, $\frac{3}{8}$ in. in diameter.

pronounced also, particularly in castings, due to coring of individual grains. Furthermore, the melting point is lowered and as a consequence, even though stronger at lower and medium temperature ranges, these 50-50 alloys become hot-short at lower temperatures than do the alloys of lower chromium content.

At higher temperature, the proportionately greater strength of alloys over the pure metals is shown by curves *B* and *C* and at some more elevated temperature by curve *D*—the two metals themselves might be too soft to carry their own weight, while an alloy of these same metals would have considerable load-carrying ability as shown.

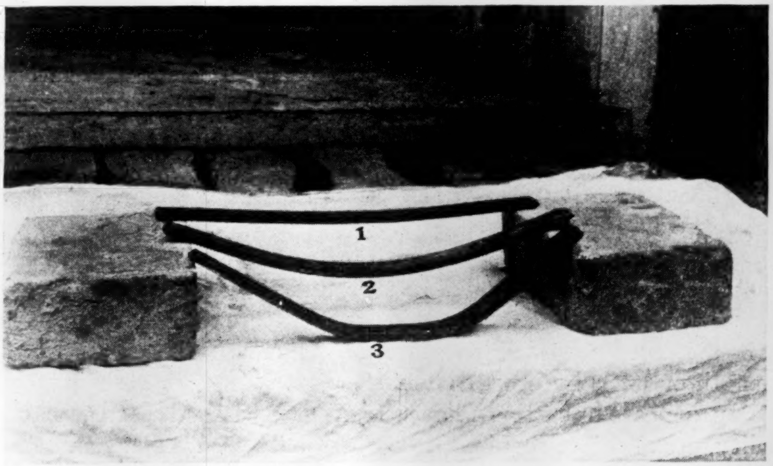

FIG. 3.—Photograph of Test Bars, Showing Relative Performance Under Load at High Temperatures of Various Alloys.

No. 1.—Fahrite N-1 (35 per cent nickel, 17 per cent chromium).
No. 2.—Chrome-Iron (18 per cent chromium, 2.4 per cent carbon).
No. 3.—Fahrite C-S (25 per cent chromium).

In certain alloys, strength increase S_2–S_1 can be attained by the addition of a third or fourth constituent; the maximum so obtained is often higher than that possible in a simple binary alloy.

The author has investigated practically every feasible combination of nickel, iron and chromium in binary, ternary and more complex combinations of these with other elements with a view to securing high physical strength at high temperatures and found that the highest values for physical strength combined with other necessary properties were included within a rather small area on the ternary diagram—around 35 per cent nickel with 16 per cent chromium.

The alloy of this composition has far greater load-carrying ability at high temperatures (see curve for Fahrite N-1, Fig. 8) than any of the higher nickel or chromium-iron compositions (see curve for Fahrite C-S, Fig. 8) and this high-temperature strength is accompanied by a degree of low-temperature toughness and ductility not available in any other composition of this class that the author has investigated. The ductility is very well illustrated in Fig. 2.

In illustration of the practical meaning of the principles involved here and to show the relative performance under load of alloys of different high-temperature strength the photograph (Fig. 3) of test bars is included. No. 1 thereon is the Ni-Fe-Cr alloy described above and for which strength values are given on the upper curve of Fig. 8. Test bar No. 2 is chrome-iron, with 18 per cent chromium and 2.4 per cent carbon, an alloy in which resistance to oxidation at high temperatures is not present to a sufficiently high degree to permit of advantage being taken of the high physical strength developed at temperatures up to 1800° F. No. 3 is the low-carbon iron-chromium base alloy for which strength values are shown on the C-S curve of Fig. 8.

A very high degree of strength in heat-resisting alloys cannot be economically secured in rolled or structural forms because of inability to work material beyond certain temperature and hardness limits. It is possible, however, to materially increase the useful working strength of steels by proper alloying.

In the case of castings, however, in uses where ductility, machineability, etc., are not required, it is possible to secure high-temperature strength and hardness to a remarkable degree. Certain alloys of the tungsten group metals for instance, which were tested under transverse load, gave a modulus of rupture of 2800 lb. per sq. in. at 2300° F. This alloy, however, was brittle when cold and very difficult to cast.

There has been considerable loose prediction respecting heat-resisting alloys of the future, but in view of the limited number of constituents from which such alloys can be made and the limited range of properties of these constituents themselves which can in turn be imparted to alloys, any probability of materials having properties differing radically from those with which we are now familiar, is decidedly remote. As previously noted, greater values for some one specific property can no doubt be secured, but on the strength of what is now known about metals and alloys it does not seem likely that compositions will be forthcoming which will combine to a much higher degree the various desirable and necessary properties than do the materials now available.

Series Number.	Group Number																
	1	2	3	4	5	6	7	8			1'	2'	3'	4'	5'	6'	7'
I	HYDROGEN 1.008 -258.0	<-- Atomic Weight <-- Melting Point															
II	LITHIUM 7.03 186.0	BERYLLIUM 9.1 900.0	BORON 11.0 2200?	CARBON 12.0 ?											NITROGEN 14.04 -210.0	OXYGEN 16.0 -235 ?	FLUORINE 19.0 -223.0
III	SODIUM 23.5 97.0	MAGNESIUM 24.36 651.0	ALUMINIUM 27.1 658.0	SILICON 28.4 1400.0											PHOSPHORUS 310 440	SULFUR 32.06 {120} {114}	CHLORINE 35.45 -102.0
IV	POTASSIUM 39.15 62.0	CALCIUM 40.7 805.0	SCANDIUM 44.1 1400.0	TITANIUM 48.1 1850 ?	VANADIUM 51.2 1750.0	CHROMIUM 52.1 1505.0	MANGANESE 55.0 1225.0	IRON 55.9 1520.0	COBALT 59.0 1490.0	NICKEL 58.7 1450.0	COPPER 63.6 1083.0	ZINC 65.4 419.0	GALLIUM 70.0 30.0	GERMANIUM 72.5 900.0	ARSENIC 75.0 800	SELENIUM 79.1 217.0	BROMINE 79.96 -7.0
V	RUBIDIUM 85.4 38.0	STRONTIUM 87.6 830.0	YTTERBIUM 89.0	ZIRCONIUM 90.7 1600.0	NIOBIUM 94.0 2100 ?	MOLYBDENUM 96.0 2500 ?		RUTHENIUM 101.7 2000 ?	RHODIUM 103.0 19000?	PALLADIUM 106.0 1550.0	SILVER 107.93 961.0	CADMIUM 112.1 321.0	INDIUM 114.0 155.0	TIN 118.5 232.0	ANTIMONY 120.0 630.0	TELLURIUM 127.6 451.0	IODINE 126.5 114.0
VI	CAESIUM 123.0 28.0	BARIUM 137.4 850.0	LANTHANUM 138.0	CERIUM 140.0 645 ?	TANTALUM 183 2900?	TUNGSTEN 184.0 3200.0		OSMIUM 191.0 2700.0	IRIDIUM 193.0 2300.0	PLATINUM 194.0 1755.0	GOLD 197.2 1063.0	MERCURY 200.3 -39.0	THALLIUM 204.1 302.0	LEAD 207.1 327.0	BISMUTH 208.0 270.0		
VII		RADIUM 225.0		THORIUM 232.5 1700 ?													

FIG. 4.—Elements Arranged According to Modified Periodic Table, Showing Possibilities for Alloying Constituents.

In order to help visualize the field of possibilities in alloys for high-temperature uses, the more common elements are shown in Fig. 4, arranged on a modified form of periodic table, in which the inter-relationship existing among the metals themselves is more apparent. A heavy line has been drawn around a group of elements outside of which it is useless or infeasible to search for even modifying alloy constituents.

The properties of all elements are too well known to require further consideration here. It is clear also that aside from copper, nickel, cobalt and iron, there are no other metals which can serve as major constituents of heat-resisting alloys for general, large-tonnage, low-cost application. It is in some combination of these more common metals with other elements of this group or between the other metals themselves that highly developed special properties should be sought.

STRENGTH-TEMPERATURE RELATIONSHIPS

The design of alloy units or assembled mechanisms for use at high temperatures is based largely, just as in normal engineering practice, upon strength of materials. Other properties of alloys, as thermal expansion rates, specific heat, thermal conductivity, or chemical stability, must of course receive far greater consideration in the design of high-temperature equipment than in ordinary structural engineering, and in many cases, these other factors may actually determine final design, but the first and basic requirement is that of physical strength at the proposed operating temperature.

The relatively rapid decrease in physical strength in all metals with rising temperatures is not in general properly appreciated by designers and users of high-temperature alloy equipment. It is not generally recognized, either, that the time factor becomes predominant in determining allowable stresses and that the calculation of stresses which will probably be encountered in service is tremendously complicated by thermal dimensional changes up to fifty times greater than those met with under ordinary atmospheric conditions, and further, that the degree and distribution of these thermal stresses are quite dependent in turn upon such other properties as specific heat, thermal conductivity, or radiation characteristics, and also upon such operating conditions as affect heat transfer or distribution.

The consideration at this point of the general relationship between temperature and physical strength of metals and alloys (exclusive of other properties) will be divided into two parts, the first being given only a few words. These divisions of the subject might be assigned definite temperature limits, with a "high-temperature" range, and a "low-temperature" range, but it is believed that the following division based on the different kinds of strength which may be possessed by metals and alloys, will be more logical:

A. Unstable Strength-Time-Temperature Relationship;

B. Stable Strength-Time-Temperature Relationship.

A. UNSTABLE STRENGTH-TIME-TEMPERATURE RELATIONSHIP

The first division includes materials with temperature and stress limits within which strength is due in large part to:

1. Strain-hardening ("cold work"); or
2. Retention, by means of sudden cooling, of a phase or constitution relationship normal to a higher temperature.

Pure metals can be strengthened materially by means of cold working. Alloys likewise can be strengthened by cold deformation and can also be made to withstand greatly increased stresses by means of suitable heat treatment. Steels are alloys of this class which includes most of the tools and structural elements of great strength used in modern industry.

1. *Strain-hardening Strength.*—When cold-worked metals or alloys are heated to a sufficiently high temperature (different, but characteristic for each), recrystallization takes place and all strengthening effects due to strain are removed. The temperature required to completely anneal any materials of the heat-resisting class is so very low, however (a few hundred degrees at most for long time treatment), that strength of this kind is not available for use at high temperatures.

2. *Quench-hardening Strength.*—Alloys in the quench-hardened state are in a condition of unstable equilibrium and the tendency to resume a normal, stable phase or constitution relationship increases rapidly with rising temperature. In the case of carbon or alloy steels a very short time exposure near the critical points will completely remove all additional strength due to quenching. As the time of heating is increased progressively, the same effect is produced at lower and lower temperatures until under conditions of sustained temperatures as encountered in high-temperature processes, it is doubtful whether any of this quench-hardening strength may safely be employed. In any case, sustained temperatures necessary to completely anneal alloys in this class are so low as to completely eliminate this kind of strength at a few hundred degrees, or certainly far below what are classed as "high-temperatures." For safety, alloys of this class should be heated before use to a temperature higher than the maximum which will be encountered in service.

B. STABLE STRENGTH-TIME-TEMPERATURE RELATIONSHIP

In this class are the pure metals and all alloys which maintain practically the same constitution or phase relationship at all temperatures. The strength of materials in this class is, in general, lowered by increasing temperatures, but is constant for a given temperature, and temperature-strength values in repeated tests or with progressive rising or falling temperatures for these tests will fall always on or near the same curve; provided, of course, that temperature is the only variable.

Well annealed alloys (steel) of Class *A* may also be included under this head provided a temperature change or a temperature gradient through critical points does not have a harmful effect.

1. *Stress-Strain-Temperature Relation.*—Assuming now that only metals and alloys of Class *B* are suitable for use in the construction of high-temperature equipment, the study and illustration of temperature effects are less difficult. The physical properties at high-temperatures of such metals as iron or nickel, or the so-called "heat-resisting" alloys, will be better understood if one considers that as the temperature rises, these metals change in general physical characteristics to resemble first copper, then aluminum, lead and mercury, as they approach and finally pass melting temperatures. Heating to higher temperatures is accompanied by an increase in thermal expansion rates and specific heat, while the ultimate and elastic strength and modulus of elasticity decrease, all approaching corresponding values for the less refractory metals. Lead, tin and zinc have practically no elastic strength at ordinary temperatures and neither has soft steel at say 2300° F. The elastic strength of annealed copper at normal temperatures is disputed but may be compared with that of steel (or iron or nickel) at say 1800° F.

In further comparison, lead or tin cannot be materially hardened by cold-working and, similarly, plastic deformation in iron or nickel or steel or heat-resisting alloys at high temperatures will be continuous with constant stress when the temperature has exceeded that at which the so-called "elastic limit" or yield point is equal to the applied stress.

2. *Stress-Strain-Temperature-Time Relation.*—Fig. 5 attempts to show the relationships which exist among temperature, time, stress and strain for typical metals or alloys of both unstable and stable classes.

When ordinary metals or alloys are broken under normal quick-pull tension-testing conditions, their breaking strengths will decrease with the temperature as shown by the Curve *A-A*. The curves of Fig. 6 show temperature-strength relationships for a number of well-known materials. The values shown thereon are typical for stresses applied rapidly and continuously to complete failure, and while not by any means indicative of allowable working stresses these curves do illustrate the effect of temperature upon strength in general.

In Fig. 5 the curve *E-E* represents a typical variation of yield point with temperature. This value is very indefinite however, particularly at higher temperatures, and is practically undeterminable

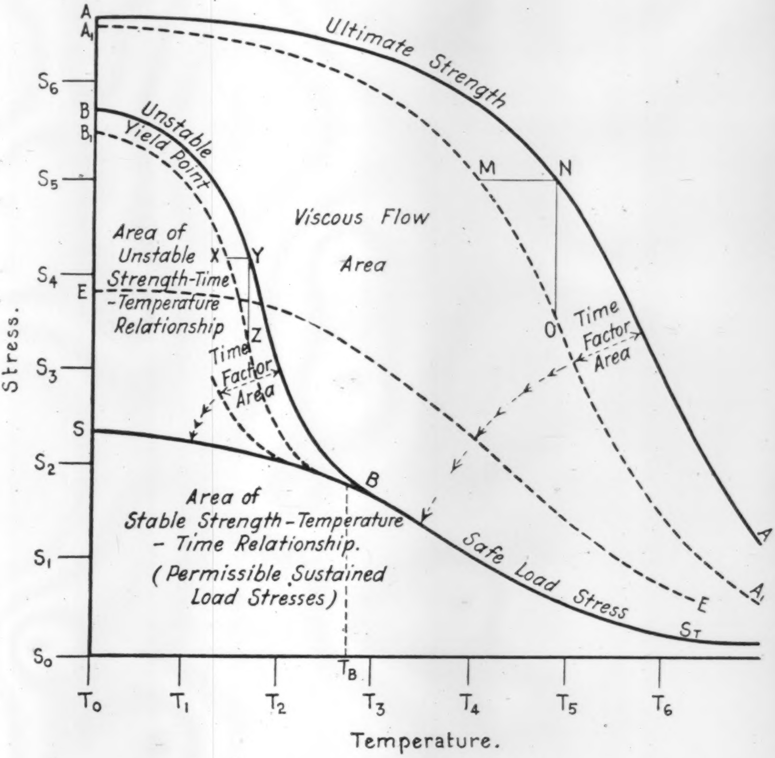

FIG. 5.—Stress-Strain-Temperature-Time Relation.

with extremely low rates of stress or temperature increase, so it had best be entirely disregarded in a consideration of metals at high temperatures.

The author has found that values for ultimate strength and apparent yield point obtained in short-time tests at high temperatures do not measure the ability of an alloy to carry sustained loads at corresponding temperatures over long periods of time. His experience with metals and alloys maintained under continuous stress for long periods of time at various temperatures furnishes strong arguments against the existence of any true elastic limit at any temperature and in favor of a real viscous flow under stress at all temperatures.

But whether metals do or do not show a continuous progressive deformation under stress is of little practical interest when it is known that for a given industrial application at low or high temperatures one may usefully employ a certain maximum stress below which deformation is so slow as to be unmeasurable or, at least, not harmful, throughout the service life of the metallic unit.

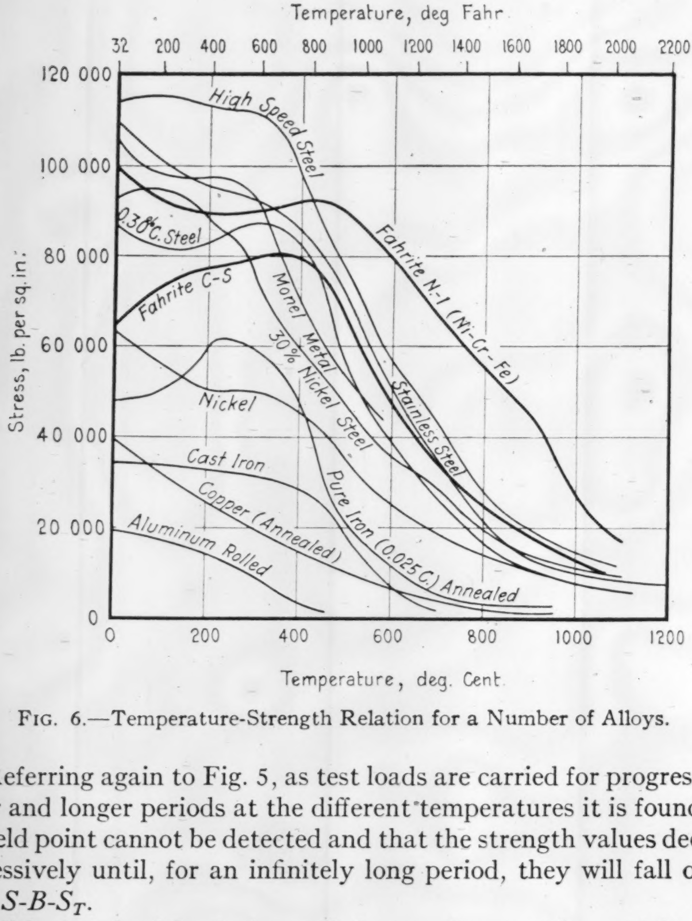

FIG. 6.—Temperature-Strength Relation for a Number of Alloys.

Referring again to Fig. 5, as test loads are carried for progressively longer and longer periods at the different temperatures it is found that the yield point cannot be detected and that the strength values decrease progressively until, for an infinitely long period, they will fall on the curve S-B-S_T.

With sustained loads for periods covering months, and in many cases years, it is found that with stresses up to line S-B-S_T (or at quite low temperatures for heat-treated steels up to S_T-B-B, S_T-B-B_1, etc.)

no, or very little, deformation occurs, but that with higher stresses appreciable continuous flow takes place. Hence, the time factor has lowered curve A-A to the position S-B-S_T.

Curve S-B-S_T does not represent definite yield point stress values for any temperature, but is intended to represent safe-load stresses below which deformation rates are too slow to be objectionable in practice. These curve values do not include a factor of safety and do not provide for additional stresses due to thermal expansion thrusts. With stresses above this curve for any given temperature higher than T_B, continuous flow takes place.

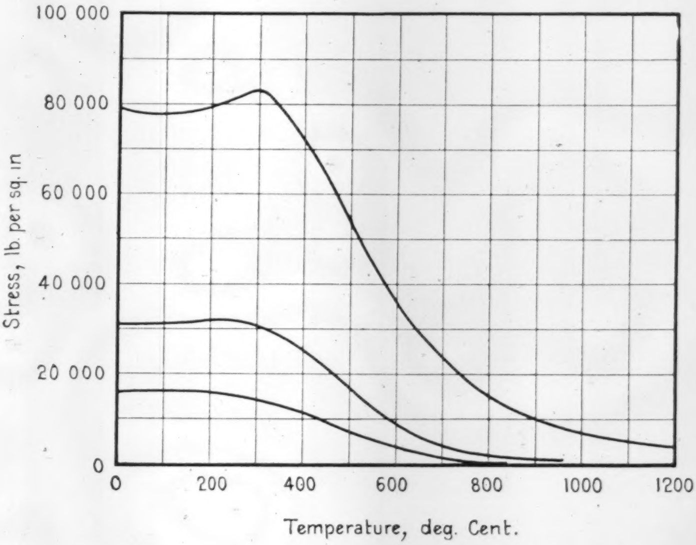

FIG. 7.—Temperature-Strength Relation for 0.3-per-cent Carbon, 3.5-per-cent Nickel Steel.

It is thus seen that, regardless of whether metals and alloys at high temperatures deform continuously under stress by viscous flow or whether they behave as plastic materials with a definite minimum stress-flow value for each temperature, they do possess a definite load-carrying ability which will, within definable temperature and stress limits, be accompanied by deformation so very small that it may be disregarded for all practical purposes.

Fig. 7 shows corresponding curves for 0.3-per-cent carbon 3.5-per cent nickel steel. The upper and middle curves represent ultimate strength and so-called yield point under quick-pull conditions, while the lower curve shows the maximum sustained stresses which the author has used for this steel at various temperatures.

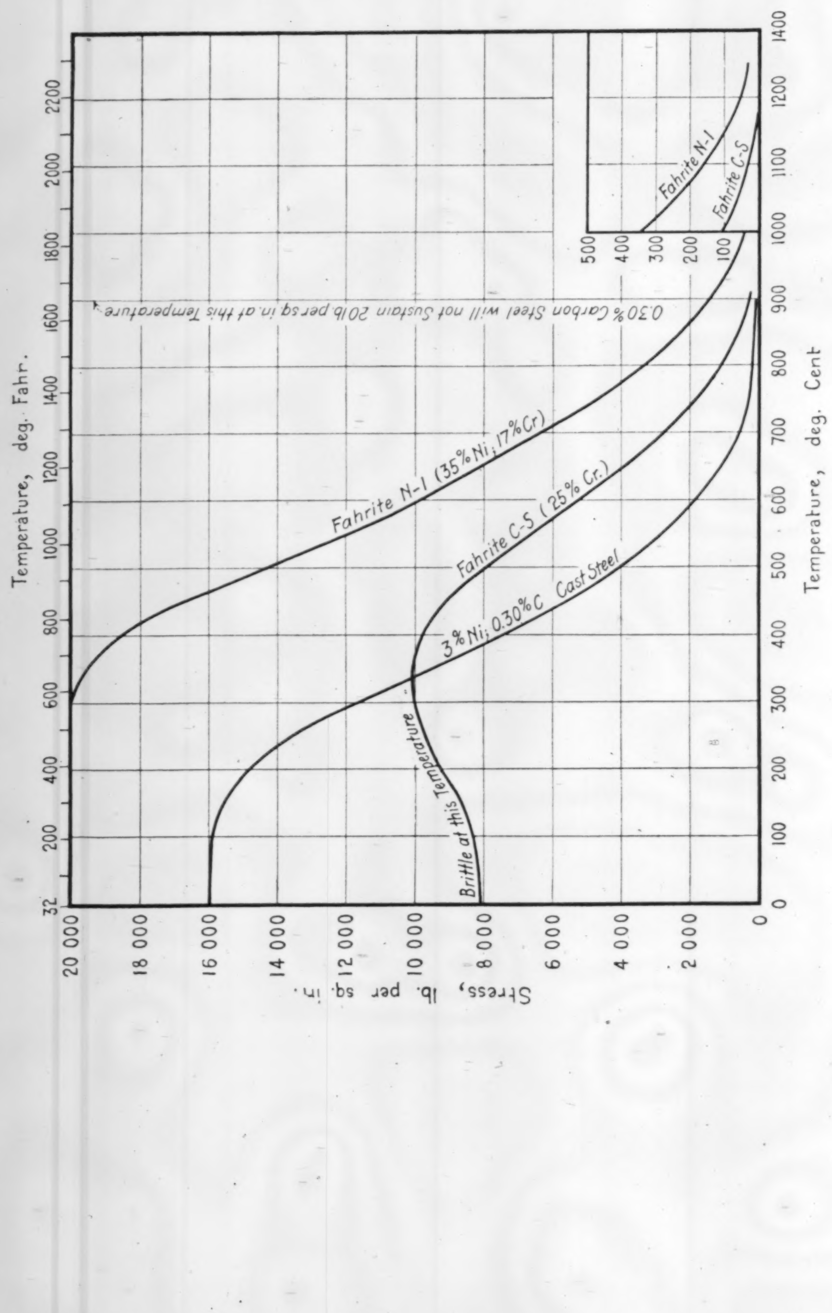

FIG. 8.—Design Strength Values for Heat-Resisting Alloys at Various Temperatures.

Fig. 8 gives values which have been successfully employed for a number of years in the design of heat-resisting alloy equipment for use at widely varying temperatures. These curves were derived largely from values secured through calculation of stresses imposed on structural members in practical commercial service in many hundreds of installations, and represents information collected from performance of the alloys during the past six years. A stress-temperature relationship in any operating unit that produced no serious deformation after a year of service was indicated as within the limit of safety; where appreciable deformation occurred the stress-temperature point was considered to be in the area of viscous flow. The curves for Fahrite N-1 and C-S were drawn between points so obtained from several hundred stress-value calculations and have been repeatedly checked by long-time tests under laboratory conditions.

Values for hardness have not been determined at sufficiently close temperature intervals to justify final conclusions but those which have been obtained indicate that under sustained loads a curve for Brinell hardness would probably parallel the curve for safe load stresses. In similar manner a scleroscope hardness curve would be closely related to the curve for ultimate strength in quick-pull tests.

To actually determine the sustained-load-carrying ability of metals through long-time tests is a very laborious procedure, but it is probable that for each composition a series of short-time tests can be devised which will give varying values from which performance outside the range of actual test conditions can be plotted or calculated. Dickenson[1] has attempted to do this and his results in plotting temperature against the logarithm of time required to produce failure, point to a solution of the problem. The author has attempted to attain a similar end by varying the rate of load application about as follows:

If, in a high-temperature tension testing machine equipped for widely varying rates of load-application, failure is caused to occur in say thirty seconds, the load required will fall on curve A-A of Fig. 5. If the rate be decreased to one-tenth, for instance, the load required will fall on curve A_1-A_1. If the machine speed be reduced progressively from one test to the next, it is found that the successive breaking (or stretching) stress values will be lower and lower and finally approach line B-S_T; so that it should be possible to calculate the change in viscosity to the stress productive of practically zero rate of flow.

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[1] *Journal*, Iron and Steel Inst., Vol. 106, p. 103.

THERMAL EXPANSION AND CONTRACTION

If metallic equipment intended for use at any required high temperature could be fabricated and operated and maintained at some specific high temperature and at no time subjected to greater temperature fluctuation than is encountered under atmospheric conditions, the problems involved in design or operation would be no more difficult than in ordinary engineering practice under normal conditions which involve only surface stability and strength of materials. The necessity for going back and forth from atmospheric to operating temperatures is the one factor which, more than any other, limits the service life of metallic high-temperature equipment.

Stresses (compressive, tensile, or shear) due to unequal temperature distribution and non-uniform temperature gradients, cause more failures in high-temperature alloy equipment than all other influences combined amounting, in the author's experience, to about 90 per cent of the total number of cases. And it is destructive chiefly because the engineer does not include in his design proper allowance for or provision against temperature inequalities or because the operator imposes temperature differentials which cause localized dimensional changes with accompanying stresses greater than the elastic strength of the alloy at the given temperature.

The extreme importance of this factor in design or operation is better appreciated when it is considered that fluctuations of only a few degrees under atmospheric conditions cause buckling or cracking of massive concrete structures such as pavements or bridges and dangerous stresses in steel structures unless suitable provision has been made for thermal expansion and contraction. And in high-temperature engineering, dimensional variations are up to fifty times as great as those encountered in ordinary structural engineering.

Warping or buckling and cracking of flat surfaces are certain to result when repeatedly subjected to intense local heating. Most failures in service from these causes are due to thermal expansion stresses which exceed the elastic limit, thus producing plastically deformed areas under either tension or compression which are then "set" for the highest temperature of a given operation cycle but again caused to flow (or perhaps fail) under reversed stresses when the temperature is lowered.

With each temperature cycle this is repeated with a similar localized plastic flow which will be either (1) alternating compression and stretch, or (2) cumulative compression or elongation depending upon whether the structure as a whole is rigid or deformable, respectively.

Cause of Cracking and Checking of Alloys in High-Temperature Service.—In rigid members, where this plastic flow is alternately compressing and stretching past true elastic limits due to thermal expansion and contraction, cracks are certain to form after a given number of reversals. Whether this phenomenon, occurring at temperatures where strain-hardening is impossible, corresponds to the ordinary "fatigue" failure under alternating stresses, is an unanswered question.

This effect, and its cause, are typically shown in the cracking of alloy carbonizing boxes, furnace hearth plates, or other rigid units in high-temperature service. In devices of this type, service-life would be very great indeed if failure resulted only from surface deterioration. In some designs and with certain alloy compositions there will be some warpage, but most failures in heat-resisting alloys are due to cracking because of the great rigidity and low ductility; the more ductile steel fails usually through warping. Alloy carbonizing boxes for example, will appear in perfect condition after 1000, 2000, 4000, or even 10,000 hours, and then within a few hundred hours more will fail completely.

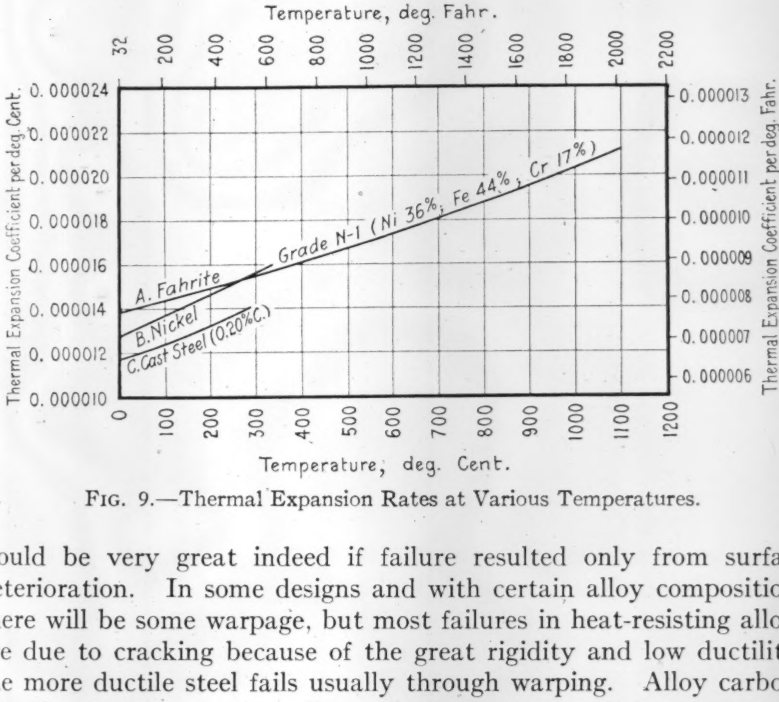

FIG. 9.—Thermal Expansion Rates at Various Temperatures.

In failures from this cause, the fracture is always granular in appearance, and in all cases examined, this rupture followed intercrystallin boundaries, due perhaps to failure of either a more fusible and less strong inter-granular eutectic or an amorphous inter-crystallin material.

The author has found that alloy compositions which will withstand the greatest number of reversals in a specially devised high-temperature bend test will best withstand the conditions of carbonizing box service. In this test, flat specimens are bent to a radius which will impose roughly the maximum amount of deformation which can be produced by thermal expansion or contraction.

Warping, buckling or bulging due to a series of cumulative plastic deformation caused by excessive alternating temperature stresses often is, but must not be, confused with sagging, bulging, or other form changes due to lack of physical strength at high temperatures.

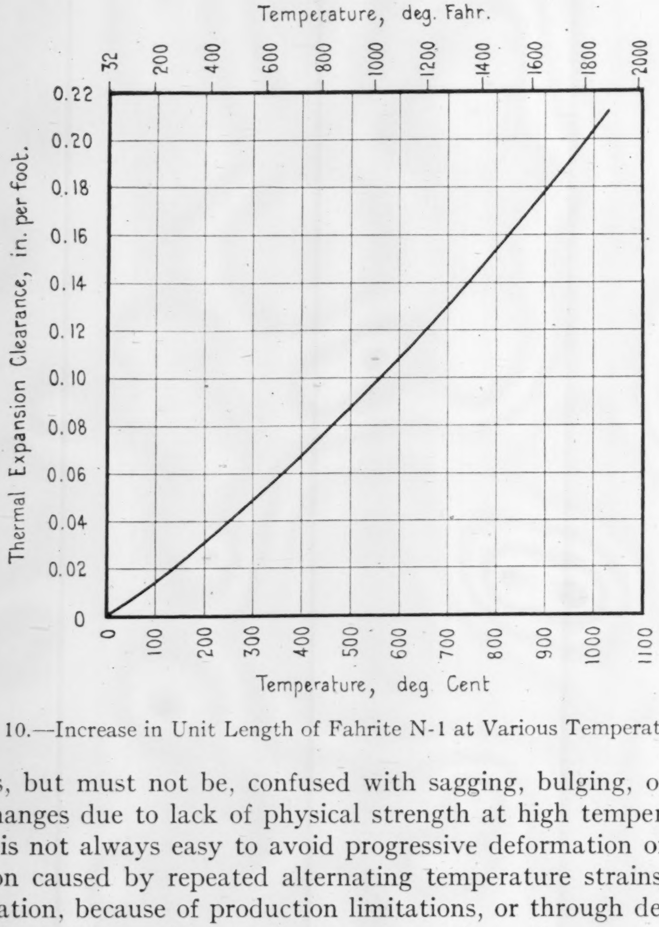

FIG. 10.—Increase in Unit Length of Fahrite N-1 at Various Temperatures.

It is not always easy to avoid progressive deformation or disintegration caused by repeated alternating temperature strains either in operation, because of production limitations, or through design or materials, so in most high-temperature operations where temperature fluctuations or gradients are necessary this destructive force must be accepted as inevitable and an everlasting "heat-resisting" alloy as impossible to secure.

Expansion Data.—Stresses and strains due to contraction or expansion with changing temperatures cause trouble also if one metal or alloy unit is welded or otherwise rigidly joined in an operating assembly with other materials having different thermal expansion rates. This condition can nearly always be avoided in design, provided accurate data concerning the thermal expansion of the various materials in the temperature range of the process is available. The rate of expansion for all materials changes with the temperature and is usually greater at higher temperatures. This change in rate of expansion or "temperature coefficient" of thermal expansion is not the same for a given material throughout all temperature intervals.

Fig. 9 gives the thermal expansion rate curve for Fahrite together with curves for several other materials in comparison. It is quite apparent from these that expansion allowances based on the room temperature figures ordinarily given in tests or in trade literature will be extremely low and structures designed from such figures will fail through compression thrusts.

Expansion data for Fahrite N-1, in more convenient form, is shown in Fig. 10; the curve indicates actual increase in unit length at different temperatures. While the rates of expansion for this alloy do not coincide at all temperatures with those for steel, its over-all thermal expansion at 1700° F. is identical with that for 0.25 per-cent-carbon cast steel.

"Permanent Heat Growth."—It is well known that cast iron suffers progressive and permanent growth when used at high temperatures. Alloys of chromium with iron-group metals show no permanent set when cooled after high-temperature service, regardless of time, unless subjected while hot or while heating or cooling, to stresses past the safe-load limit for any temperature. Stretching due to excessive loads or to rigid construction often occurs in the case of heat-resisting alloys and this has been erroneously reported as a "growth" corresponding to that characteristic of cast iron. Long, cylindrical, rotating alloy retorts for example, supported only on trunions at each end have been observed to increase in length if operated with excessive load stresses. The growth, in this case, however, is due to a somewhat lower rate of flow under compression than under tension or to a somewhat higher yield or flow point under compression, and if the load stress is slightly above the safe-load tensile strength, an infinitesimal stretch of the material with each revolution will result with consequent progressive increase in length. In this case it is obvious that under non-rotating operations the cylinder would sag rapidly.

Whenever, therefore, a case of permanent growth is reported in alloys, the cause should be sought somewhere outside the alloy itself, and in most cases faulty design may be blamed.

Effect of Critical Points.—In the case of iron or nickel or their high-percentage alloys, there is one other form of dimensional change due to change in temperature, which complicates stresses due to fluctuating temperatures. At near 300° C. for nickel and above 700° C. for iron, critical points due to an allotropic change occur and are accompanied by rather abrupt changes in rate of expansion. In the case of either metal, a temperature gradient or a change through this critical point will set up stresses of considerable magnitude.

In properly balanced "heat-resisting" alloys of these metals with chromium and other components, these effects are not encountered.

SPECIFIC HEAT AND HEAT CONTENT

In most high-temperature chemical and metallurgical processes, containers or conveying units are alternately heated and cooled through temperature intervals often as great as 2000° F. In such cases it is always desirable and often necessary to know the specific heat or heat-absorbing capacity of these operating units in order to render possible the computation of heat transfer and heat losses.

The specific heat of metals and alloys varies with the temperature, and usually increases as the melting point is approached. The rate of increase, or temperature coefficient, is not necessarily the same at all temperatures, but for most practical purposes these temperature variations can be shown on a smooth curve.

There is a dearth of accurate data regarding the heat capacities of materials at high temperature, and most of what is available neglects to give exact temperature limits within which stated values are true. Even alloy manufacturers have made a practice of giving specific heat figures (as in the case of thermal expansion) for low temperature ranges only. The value of accurate heat-content data is apparent from a casual study of ordinary steel-treating operations.

Many hundreds of tons per day of carburizing and annealing containers of various types are heated to say 1800° F., and allowed to cool in the open air with a resulting heat loss per heat cycle of nearly 290 B.T.U. per pound or 580,000 B.T.U. per ton of container metal. As the weight of container is often greater than that of the charge being treated this extra cost in terms of coal or oil or dollars is quite an important item.

Inter-Related Properties.—Other important properties which are tnier-related with specific heat and with which it must be correlated in design are physical strength, thermal-conductivity, and heat-emissivity or absorption factors. Surface conditions due to corrosion also have some effect in determining whether an alloy unit will accumulate or give out its full capacity for heat with each temperature cycle, and this is affected also by the time of each cycle or by the rate of temperature change.

Effect of Physical Strength on Heat Losses.—The cross-section of an alloy unit or structural member is often determined by its physical strength at operating temperatures. It is quite obvious that the stronger the alloy the less weight will be required to carry a given load, with correspondingly lower heat losses per cycle of operation.

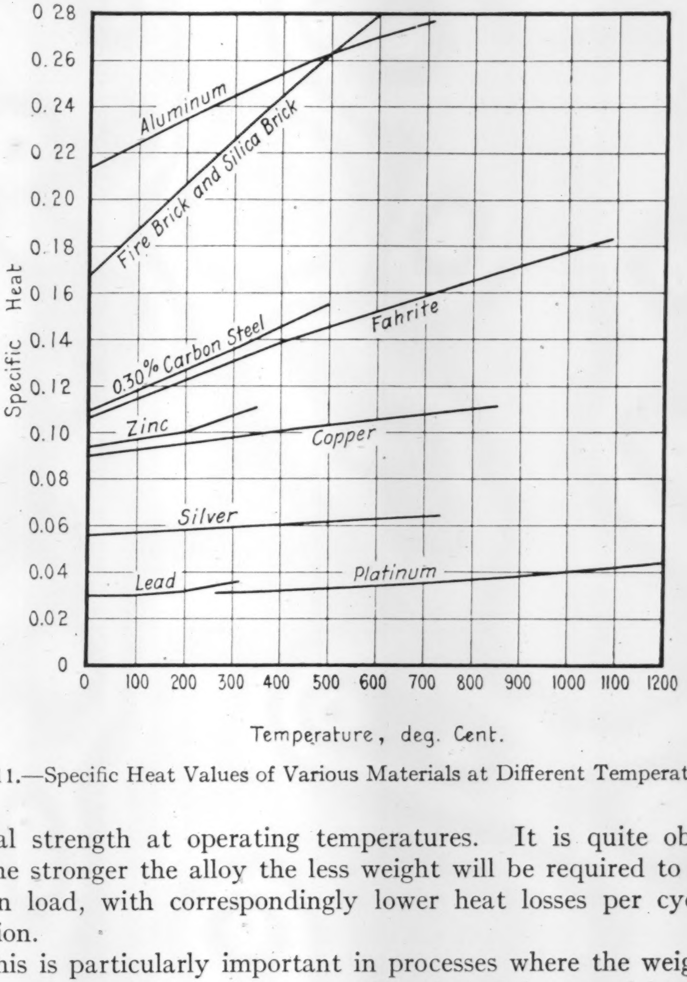

FIG. 11.—Specific Heat Values of Various Materials at Different Temperatures.

This is particularly important in processes where the weight of containers or carriers may be greater than that of the material treated. Typical examples of this are the alloy point bars used to support thin

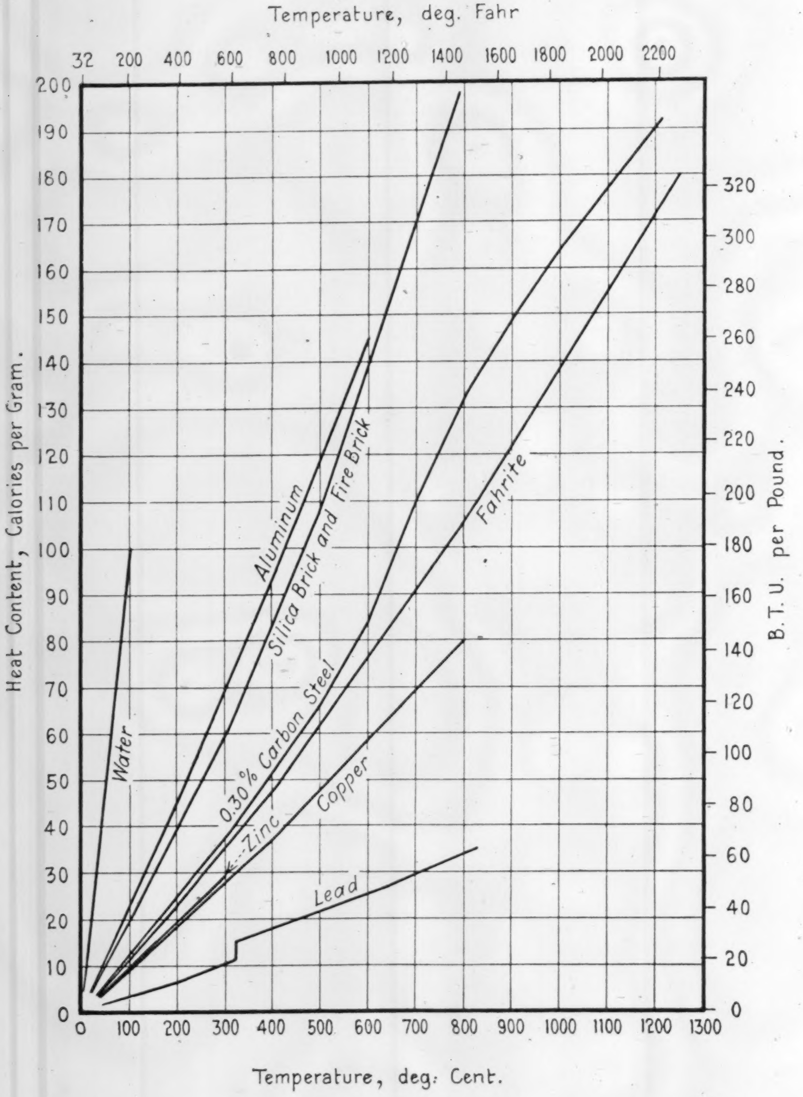

FIG. 12.—Increase in Heat Content of Various Materials Above 0° C.

sheet steel in enameling operations, and alloy conveyor systems of continuous heat-treating furnaces.

Effect of Thermal Conductivity, Emissivity and Absorption Coefficients on Heat Losses.—The intrinsic thermal conductivity of a metal or alloy or its heat emissivity or absorption power influences heat losses only in so far as they may affect the rate with which a metallic unit may approach the temperature of its surroundings on either heating or cooling.

Rapid heating or cooling may be desirable in one case and very objectionable in another, so no general statement can be made in this connection either for or against given values for these properties except on the basis of merit in each individual problem.

Fig. 11 shows plotted values for the specific heat of Fahrite N-1 with curves for steel and ordinary refractory furnace brick for comparison. These values are relative only and can not be conveniently used in ordinary heating problems.

In Fig. 12 these same values are converted into terms of heat content in engineering units and from these curves heat losses can be read directly for any given temperature interval. These curves are average values for materials of ordinary commercial degrees of purity and are plotted from figures which have been either determined or checked for the author's own use.

HEAT-TRANSFER FACTORS: THERMAL CONDUCTIVITY (K), RADIATION, CONVECTION HEATING, OVER-ALL HEAT TRANSFER RATE (H)

In many high-temperature processes requiring the use of metallic units, the question of heat transfer is of vital importance. Probably in no other phase of high-temperature engineering has available data been so complicated with mathematical equations, which are of great value in abstract consideration of some single phenomenon under restricted conditions, but of decidedly limited and difficult application in the solution of industrial high-temperature problems under conditions involving many variables of operation and production.

Complicated equations representing laws for thermal conductivity and emissivity are of little service in overcoming difficulties encountered in ordinary every-day high-temperature industries in which design and operation and responsibility for profit are in the hands of men who do not have the time or the specialized ability to work out the practical application of abstract laws. What is needed in the way of information to further progress in this field is practical simplified data from a sufficient number of typical operations to form a basis of judgment in designing for conditions having a different set of variables. In many cases, however, such data cannot be used and final design of heat-transferring equipment can only be based on results of tests carried out under conditions which duplicate those of the contemplated process.

Heat-transfer is carried out by one or more of three methods:

1. Conduction;
2. Radiation;
3. Convection.

CONDUCTION AND THERMAL CONDUCTIVITY

The intrinsic thermal conductivity K of the alloy itself is usually of small importance in its bearing upon heat-transfer, but it is, nevertheless, a factor of vital importance in affecting design. For instance, in alloys with low specific conductance, the necessity for temperature equalization throughout a given unit may call for a section far heavier than required merely to give sufficient physical strength, and in many cases where thermal expansion stresses may be set up and do damage, steep temperature gradients can be avoided only through the greater heat conductance of a large cross-section.

A high thermal conductivity with more rapid heat distribution decreases danger from failure through excessive thermal expansion stresses and is very desirable from this point of view. This relationship between K and failures produced through thermal expansion is strikingly shown in the case of metal molds, in which almost invariably such a high and non-uniform temperature gradient is set up that failure invariably occurs by surface cracking or checking after relatively few castings.

Another probable example of failure due to inability of a metallic mass rapidly to distribute heat which is applied in an intense degree to the surface, is the bore-checking of high-power guns. In this case the surface is exposed to rushing gases, and no doubt to radiating particles of burning powder, at an exceedingly high temperature. The high velocity of the gas reduces the solid-gas surface film to practically zero so that heat transfer to the surface is extremely rapid. As a consequence the bore surface is raised to quite a high temperature instantaneously, and through conduction is cooled almost as rapidly. This surface heating and cooling is of course accompanied by expansion and contraction, confined largely to a surface film of metal which, after a sufficient number of reversals, with perhaps an actual strain or plastic flow, becomes covered with a maze of fine checks.

High thermal resistance, along with a paralleling high electrical resistance as compared to pure metal, is a fundamental property of alloys, however, and the very alloying elements which impart resistance to oxidation and physical strength likewise increase thermal and electrical resistivity. Hence, low thermal conductivity in heat resisting alloys must be accepted as unavoidable. Low thermal conductivity is of decided advantage, on the other hand, where heat losses through rapid distribution or saturation might otherwise be excessive, or in cases where a localized heating effect is desirable.

Values for thermal conductivity or rate of heat flow (commonly designated *K* or *k*) in B.T.U. per square foot, per inch, per hour, per 1° F. for some common materials are as follows:

Silver	2900	Cast Iron	200
Copper	2600	Fahrite	120
Aluminum	1400	Carborundum	20.2
Graphite	1000	Water	10
Iron	420	Fire Brick	6
Nickel	400	Sil-O-Cel	0.5
Lead	250	Air (Most Gases)	0.15

For corresponding c. g. s. units multiply the above figures by 0.0003445.

The thermal conductivity of most refractories increases with rise in temperature. In the case of silica brick and fire-brick, the conductivities at 2000° F. are practically double the room temperature values. For most metals and alloys, on the other hand, thermal conductivity decreases with rising temperature but the temperature coefficient for refractory alloys is fairly low, and thermal conductivity figures for lower temperature ranges may be employed, over wide ranges, with a factor of safety if desired.

RADIATION

To a far greater degree, quantitatively, than is appreciated even by the experienced designer and operator of high-temperature equipment, the transfer of heat is effected by means of radiation. The rôle of radiation is very important in processes where a wall of alloy is interposed between the source of heat and the material to be treated, so all properties of alloys which either accelerate or retard heat transfer by this method must be recognized and included in consideration of design. This is particularly true in the case of muffles and underfired hearths and with retorts or containers where heat may be absorbed by the hot-side surface and given up to the charge from the opposite surface almost entirely by radiation.

All bodies, above absolute zero, radiate energy in an amount determined by the temperature, and by the character of its surface.

Radiant energy, impinging upon a body will be partly transmitted, partly reflected and partly absorbed. Metals, however, are not transparent in mass, so direct transmission need not be considered in connection with their use at high temperature.

A considerable proportion of the heat waves striking a metallic surface are reflected and the percentage of the whole so turned off is defined as the "reflectivity factor." Polished metallic surfaces reflect most of the impinging radiant heat while such materials as carbon black or certain metal oxides, reflect only a small proportion of it. Polished silver reflects over 95 per cent and polished iron about 75 per cent while oxidized iron reflects only about 30 per cent.

A body which absorbs all incident radiant energy is defined as a "black" body. Few materials encountered in ordinary industrial high-temperature processes approach ideal black body performance and the proportion of the incident radiation which each substance does absorb is defined as its "absorption factor." Powers of absorption and emissivity for any given material are the same, so absorption values also become definite emissivity factors. These factors for some common materials at temperatures up to 700° C. average about as follows:

Ideal black body	1.00
Copper oxidized	0.70
Iron oxidized	0.60
Iron bright	0.20
Iron calorized	0.20
Silver polished	0.03
Fahrite bright	0.25
Fahrite oxidized	0.75

It is not possible to give tables or curves for heat transfer by radiation which would cover other than a restricted set of conditions because of the many possible combinations of variables. Radiation or absorption rates for oxidized Fahrite at 100° C. to surroundings at 20° C. in one test were 1.1 B.T.U. per sq. ft. per hour, per 1° F. while bright copper under the same conditions gave 0.42 B.T.U. Bare, black iron pipes at low and medium temperature ranges will radiate from 0.5 to 3.0 B.T.U. per sq. ft. per hour, per 1° F. depending upon the temperature difference between pipes and room and upon condition of the surface. These figures are quite approximate, however, and are given more for illustration than for information.

In spite of the inability to employ a single all-embracing radiation formula to every problem, such general laws as that which states that every body radiates heat in proportion to the fourth power of its absolute temperature are of universal application. This may be supplemented for use under specific conditions by those which hold true for the variables of the given application.

Results sometimes difficult to explain are encountered in radiant heating. For example, a chemical retort or container with an oxidizing high temperature on the outside and a reducing lower temperature on the inside will heat its charge more slowly, or assume an average temperature nearer that of the high side, than if oxidizing on the inside also, provided that in the former case, the inside temperature is sufficient to maintain a bright, unoxidized surface. This is because the outer surface absorbs heat faster than the inside can radiate it due to the higher emissivity factor of oxidized surface over one that is bright.

Possible variations from this cause must be included in the consideration of a design based on physical strength, as otherwise a too low temperature might readily be assumed for a probable operating maximum in any contemplated process, with the accompanying use of too high stress values in structural members. In short, factors other than temperature differences have considerable weight in determining what temperature will be assumed by a metallic wall interposed between two bodies at different temperatures.

It must be remembered, also, that the emissivity or absorption factor is dependent only upon the character of the exposed oxide surface and that the amount of heat which can reach the mass of metal beneath the oxide coating or pass through it will be decreased to an almost unbelievable extent by the thermal resistivity of a thick oxide coating and still more so if the coating, even though thin, is loosely adherent with an air or gas film interposed between the scale and the metal beneath. The thermal conductivity of the alloy itself is nearly one hundred times as great as that of the ordinary oxide scale, and about 1000 times greater than for air, so the effect of a heavy scale in cutting down heat flow is quite obvious. Air is one of the best insulators known, particularly in thin films where very little circulation is possible, so a loosely adherent scale cannot pass heat through to the metal beneath as rapidly as it absorbs it on the outer surface. This hold true also for products of corrosion other than oxides.

When high chromium alloys are exposed to high temperatures, the surface oxide formed is adherent and very thin, perhaps a tenuous film only a few molecules thick. This film serves to increase the surface absorption power by three or four times without at the same time counteracting this advantage, as does the heavier oxide coating or scale such as forms on steel.

CONVECTION

High temperature transfer of heat by convection is not influenced by any known intrinsic property of alloys, unless there exists some variation in surface adsorbing power for different degrees or conditions of oxidation (which have on the other hand, such a marked effect on heating by radiation or conduction).

The rate and efficiency of heating by convection, however, is determined by the velocity and freedom of circulation of the heating or treated fluid, either liquid or gas, and these in turn are controlled by design or operation. Hence indirectly, the part played by convection in the over-all rate of heat transfer must be recognized and given proper weight in making out designs for high temperature alloy equipment.

Contact Resistance or Skin Effect.—When a fluid (liquid or gas) is in motion over the surface of a solid, a more or less stationary film or skin of the fluid adheres to the solid and the thickness of this is dependent upon the character of the fluid and upon the velocity of its flow. It has been shown that most fluids, and gases particularly, are very poor conductors of heat, so that the rate of flow of heat from fluid to fluid through a metallic wall is determined more by contact resistance of surface films than by the conductivity of the alloy itself.

TABLE I.—RESULTS OF TEST TO DETERMINE EFFECT OF GAS VELOCITY ON RATE OF HEAT TRANSFER

Furnace temperature, 1800° F.
Fahrite C-S tube 1.75 in. in inside diameter with $\frac{1}{4}$ in. wall thickness.

Temperature of Air, deg. Fahr.		Cubic Feet of Air per Hour	*H* (over-all) B.T.U. per sq. ft. per hr. per 1° F.
Intake	Outlet		
80	600	800	2.4
80	630	1200	3.8
80	650	1600	5.9

Heating by convection is retarded by this contact resistance in all cases where heat flow is:

1. Gas to and from Metal;
2. Liquid to and from Metal.

1. *Gas to Metal.*—The effect of velocity of gas flow on rate of heat transmission is illustrated in Table I, which gives the results of a test made to determine the rate of heat transfer from a furnace combustion chamber through the wall of a Fahrite pipe to air forced through the inside of the pipe.

It should be noted that at higher velocities, the larger amount of air emerged at a higher temperature, with a resulting greatly increased rate of over-all heat transmission. The curve of Fig. 13 also illustrates this phenomenon very plainly.

This greater value for *H* (over-all heat transfer factor) is due chiefly to the more turbulent air flow which reduces contact resistance by thinning down the poorly conducting film of air at the inner surface of the alloy pipe. With increasing velocities and accompanying higher rates of transfer a point would, of course, soon be reached where the additional cost of producing the higer velocities would outweigh any advantages in the way of increased rate of heat transfer. This does, however, point to a decided advantage for small-pipe, high-velocity preheating or recuperating units.

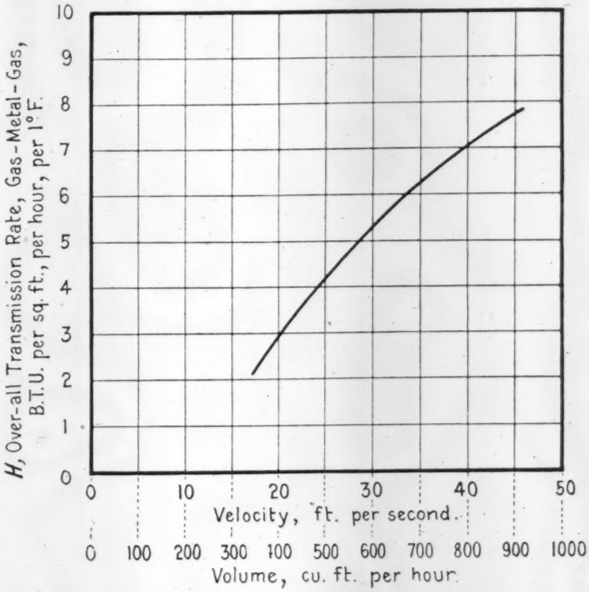

FIG. 13.—Variation of Heat Transmission, *H*, with Gas Velocity.
Fahrite pipe, 1 in. in inside diameter, $\frac{1}{4}$ in. in thickness, 30 in. long.
Furnace temperature, 2000° F.

A commonly encountered example of the thinning out of this surface contact film, with consequent more rapid heating, is seen in improper burner installations where the gases of combustion impinge with considerable velocity directly upon the surface of an alloy container—a lead pot, or retort, for example. Invariably a hot-spot results, not because the immediate outside temperature is greater but because over this area the more rapid and turbulent gas flow tends to wash this film away, and localized heating is due chiefly to more efficient transfer from gas to metal through this resulting thinner film.

2. *Liquid to Metal.*—In the case of liquids, greater viscosity results in thicker films which may in cases of very low-velocity flow, or true viscous flow, include the whole liquid mass. Molten metals or fused salts or slags are typical of liquids encountered at high temperatures, and the efficient heating of these depends upon the same laws and rules as those which govern the heating of ordinary liquids at relatively lower temperatures.

In many high-temperature processes, a third form of contact resistance due to surface films must be considered. This has special reference to steel quenching operations and has to do with the film of vapor which is formed between the two bodies when the tenperature of the solid is above the boiling point of the liquid. When heated steel parts or alloy units are plunged into water or some other quenching medium, the rate of cooling is first slow due to an intervening film of vapor whose thickness is affected by the temperature of the solid, by the velocity of circulation of cooling liquid, and by its conductivity. As heat must be carried across this vapor sheath largely by conduction, the cooling rate of the metallic unit is at first quite low, but as the temperature decreases, actual contact between solid and liquid is permitted, producing a violent boiling effect with accompanying very rapid cooling, and as the temperature decreases still farther, to below the boiling point of the liquid, the cooling rate again changes, being then dependent upon true surface conductivity of the liquid itself. In the design of units for quenching operations, these points must be considered and provision made for thermal contraction stresses which may otherwise cause failure.

OVER-ALL HEAT TRANSFER RATE—(*H*)

Heat-transfer problems generally associated with the use of metals at high temperatures involve, chiefly, heat flow from gas to solid or *vice versa*, or from liquid to solid or *vice versa*. Over-all transfer rates depend primarily upon metallic conductivity and contact resistance in convection heating and upon metallic conductance together with surface emissivity and absorption factors in radiant heating.

In spite of the many different combinations of these numerous variables that may be encountered in going from one industrial heating problem to another, a few examples will serve to illustrate what may be expected in the way of performance under given conditions.

Fig. 13 shows how heat transmission increases with rising gas flow velocity. This points to greater efficiencies through the use of small diameter pipes and higher velocities, but also to prohibitive cost when reduction in size is carried too far. Results from a similar test but with a pipe having a $\frac{1}{2}$-in. wall section gave values only about 10 per cent lower, showing that surface contact resistivity is of far greater influence than metallic conductance.

Fig. 14 shows the effect of temperature difference on the rate of heat transfer. Values here are for the specific conditions of the test but are fairly representative.

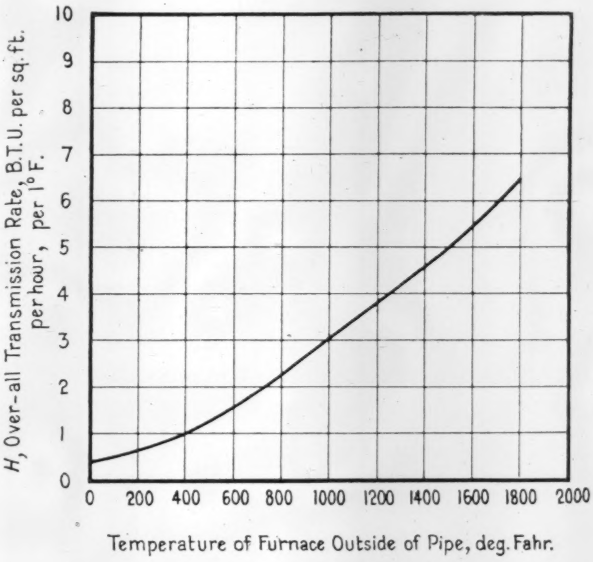

FIG. 14.—Effect of Difference in Temperature on Heat Transfer, *H*.
Fahrite pipe, 4 in. in inside diameter, $\frac{3}{4}$ in. in thickness. Air flow constant, 500 cu. ft. per minute.

In ordinary steel annealing operations where heat must pass from furnace walls and combustion gases through the steel containers to a steel charge within, a fairly representative condition gave average values for heat transmission varying from 1 to 3.

Average heat transfer rates from fuel-fired furnaces through the wall of an alloy container to molten lead will vary from about 15 to 25 B.T.U. per sq. ft. per hour, per 1° F. difference in temperature between the lead and the furnace walls and atmosphere. In the case of fused salts, it is considerably lower.

The curves of Fig. 15 show how a surface coating of appreciable thickness decreases the rate of heat flow. These curves are plotted from temperature readings on the inside of containers cast from the same pattern. The two upper curves, *A* and *B*, show rates of heat penetration for new castings while the same curve *A* and curve B_1 show rates for these containers after heating for several days at 1800° F. The alloy surface was unaffected, and after the run, the heat flow rate was found to duplicate the original curve *A*. For the steel, however, the heat-transfer rate had fallen to curve *B* due to the presence of an oxide scale about $\frac{1}{16}$ in. thick.

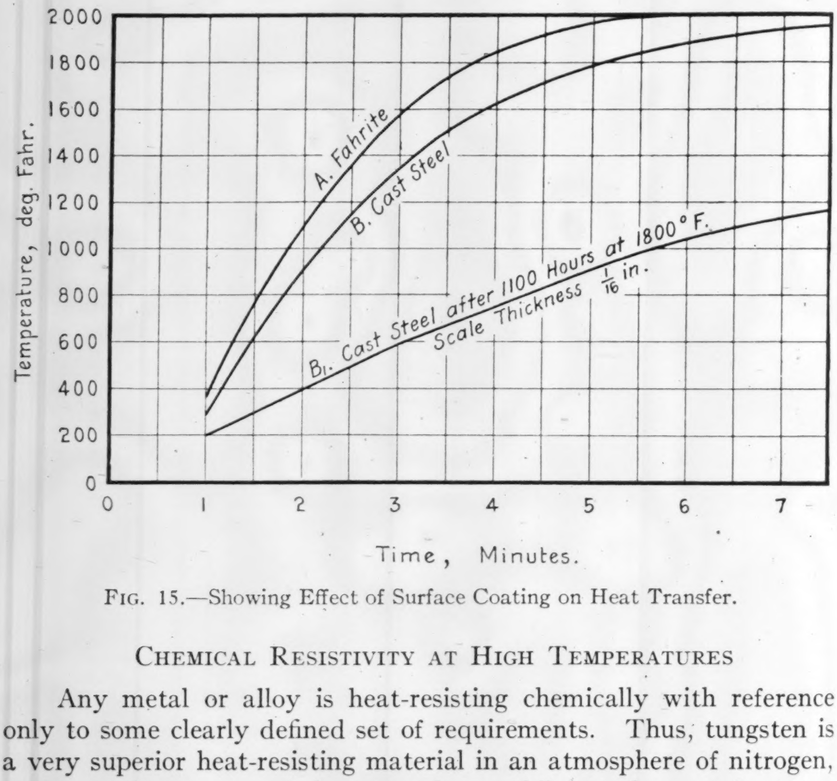

FIG. 15.—Showing Effect of Surface Coating on Heat Transfer.

CHEMICAL RESISTIVITY AT HIGH TEMPERATURES

Any metal or alloy is heat-resisting chemically with reference only to some clearly defined set of requirements. Thus, tungsten is a very superior heat-resisting material in an atmosphere of nitrogen, argon, or in a vacuum, but tantalum, while nearly as refractory, cannot be used in nitrogen, and neither of these is as heat-resisting as ordinary cast iron in open air. Platinum is very heat-resisting in open air, but in an atmosphere of CO gas or metallic vapors or in contact with certain salts it is unstable at quite low temperatures. Lead is more heat resisting than nickel or iron when in contact with sulfuric acid, and iron is a better material than platinum for lead pots.

These perfectly obvious examples, which could be multiplied many times, are given merely to illustrate the fact that in so far as resistance to corrosion is concerned any given metal or alloy is "best" with reference only to some one set of conditions. Resistance to corrosion (scaling and oxidation), however, is not the only criterion to be used in selecting equipment for high-temperature operation. If this property alone were required, it would be a relatively simple matter to meet very rigid requirements. The real difficulty lies in combining with some specific chemical resistivity the necessary physical and mechanical properties and the combination of all these into a complete working unit of proper design.

Surface stability in metals and alloys at high temperature is due either to:

1. Intrinsic inertness under conditions of exposure;
2. The formation of an adherent impervious protecting compound through non-progressive reaction between metal or alloy constituent and one or more "corrosive" agencies of environment.

Gold, silver, platinum and several other elements have been called "precious metals," chiefly because they have a high degree of surface stability at all temperatures under atmospheric conditions. Of the so-called precious metals, however, only gold and platinum have been used extensively at high temperatures, but because of high cost their field of application is decidedly limited. Some time ago the author developed an alloy of gold with palladium which gives to a high degree the refractoriness and chemical resistivity of platinum at considerably lower cost; but even this is so high as to render its use prohibitive for other than laboratory purposes.

Under proper conditions, practically any of the metals or their alloys may become more "precious" even than gold or platinum, as pointed out above.

The problems of corrosion at high temperatures are not nearly so numerous as at lower temperature ranges because of the smaller number of corrosive agencies which can exist at elevated temperatures, but they are often very difficult to solve because of far greater chemical affinities at higher temperatures, or reversible reactions and changing chemical equilibria which may be encountered, or because of mechanical difficulties in process manipulation. Several of the most common forms of high-temperature corrosion are briefly discussed below.

Only under ideal conditions are problems of oxidation uninvolved by the accelerating or retarding effects of elements other than oxygen itself. The presence of sulfur compounds, or acid or alkaline salt

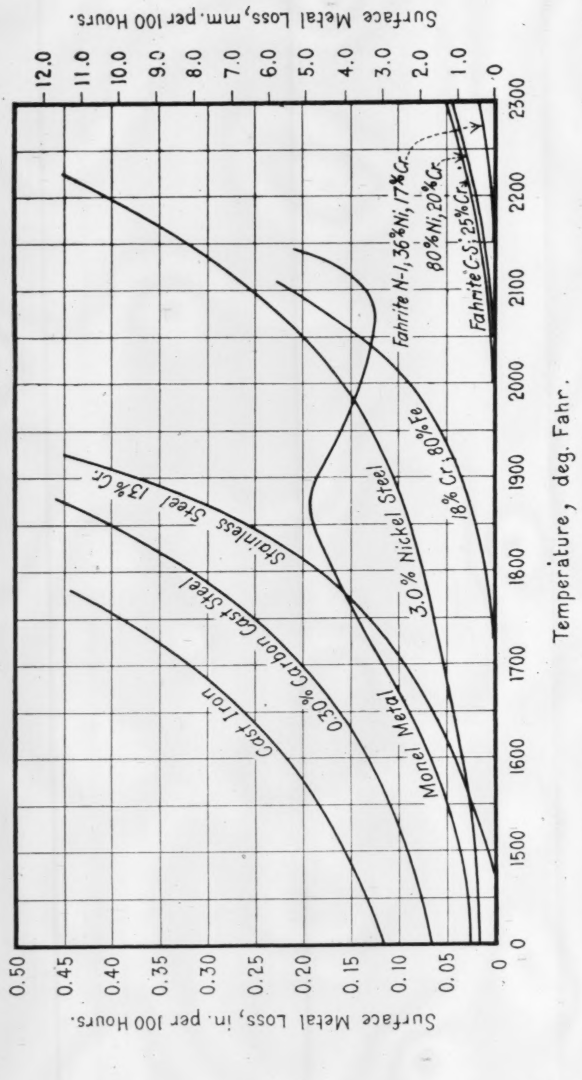

FIG. 16.—Comparative Surface Loss at Elevated Temperatures.

vapors, for example, will, even in extremely small amounts, greatly increase or decrease the rate of oxidation, depending upon what materials or conditions are involved.

The curves of Fig. 16 show the comparative surface loss rates for some well known materials at elevated temperatures. The figures from which these curves are drawn were obtained in tests carried out as follows: Test pieces of the indicated materials were heated in a gas-fired furnace with excess air. At short intervals the samples were removed, cooled, and hammered free from scale and then replaced in the furnace. At the end of each test period, the decrease in thickness was accurately determined and checked against loss in weight. This test was repeated at each of the temperatures indicated and the oxidation rates so obtained are shown on the curves. It should be noted that the millimeter figure also represents roughly the loss in grams per square centimeter per 100 hours (compare with density).

These rates have been found to be quite representative of losses for closed-muffle and electric heating also. Neither these curves nor the relationship among them, however, would be the same for these same materials if heated in products of combustion of a high-sulfur fuel. Different proportions of O_2, CO, CO_2, etc., in the heating atmosphere would also cause considerable shifting of these values.

The curves are from tests made in 1919 and have been distributed in sales literature. Dickenson gives figures[1] from later similar tests which vary somewhat from these but differences probably illustrate variations in results which may be obtained under slightly different test conditions.

In many chemical and metallurgical processes the materials or products of combustion are high in sulfur, SO, SO_2 or SO_3, depending upon the degree of oxidation. The use of high-sulfur fuels is also sometimes required and under such conditions, steel or iron or nickel are rapidly attacked. It was necessary to develop a grade of alloy which would be heat-resisting in high-sulfur atmospheres and no alloying metal has yet been found which will impart this particular type of heat-resistance as satisfactorily and economically as chromium. Fahrite C-S represents this class of iron-chromium base alloy having about 25 per cent chromium, and this gives satisfactory service even for arms and rabbles of sulfide-ore-roasting furnaces at temperatures up to 1850° F. To provide satisfactory resistance to sulfur gases, a practically nickel-free alloy is required, as nickel and its alloys are readily corroded under these conditions.

This same type of alloy happens also to give superior resistance to attack by fumes or gases containing arsenic, antimony, selenium, and tellurium and to attack by fumes of lead or by the molten metal itself or by its oxides.

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[1] Iron and Steel Inst., Vol. 106, p. 103.

In opposition to the above, no high-chromium alloy will withstand the fluxing action of fused alkali metal salts at high temperatures under oxidizing conditions because the otherwise protective chromic oxide coating reacts to form alkali metal chromates as fast as it is formed. Under reducing conditions, however, these salts do not in general attack high-chromium alloys.

These illustrations are given not so much as detailed information as to show that an alloy which is heat-resisting for one purpose may not be for another and to further demonstrate the necessity for sacrificing certain desired properties in order to combine one or more very necessary characteristics. In this case it is necessary to sacrifice ductility and toughness at lower temperatures and, to a considerable degree, physical strength at high temperatures as shown by the curve of safe load stresses for Fahrite C-S. in Fig. 8.

DESIGN

It is quite evident from the foregoing that to build structures which have to withstand the individual or combined attack of so many deteriorating influences is quite a task, and in view of the many possible combinations of variables which are encountered among the many industrial uses of high-temperature, it is not possible to give rules or instructions of general application. The design of heat-resisting alloy equipment for any particular use must allow for all the variables encountered in that particular application or the anticipated performance cannot be attained.

Proper design is not difficult, however, if underlying principles are given due consideration and if based on accurate data concerning physical and chemical properties of the materials of construction.

It must be recognized, however, that the successful use of metals at high temperature requires more than a knowledge of principles and data and that in this high-temperature field, structural materials and data concerning their properties bears about the same relationship to finished structures and operating mechanisms as do steels and their properties to bridges or automatic machines for instance. The responsibilities of the manufacturer for ultimate results (of design and fabrication) should be comparable to corresponding obligations assumed by the manufacturers of structural steels.

The steel mill is not asked to furnish with a shipment of steel a guarantee of satisfactory performance for a bridge or a skyscraper or an automobile which may be constructed therefrom. Between the producer of structural materials and the finished product, capable engineering talent is introduced upon which rests the responsibility for the developments of suitable designs and proper structures in which allowance is made for all limitations in properties of materials and necessary provision made for any peculiarities in conditions of operation.

In the case of heat-resisting alloy equipment, however, most of the materials have heretofore gone directly into operating units of such design that in most cases they are suitable only for operation under atmospheric conditions. And in such cases the purchaser usually (and wholly without justification) asks the alloy manufacturer to guarantee a definite performance or service life, often operating under conditions concerning which the manufacturer knows little or over which he has no control. It has been too widely accepted that a "heat-resisting" alloy is completely fool-proof and that structures and operating mechanisms might be made therefrom without regard to principles of engineering and of design.

The fault for this is divided. The alloy manufacturer has been at fault in not providing complete and accurate practical information concerning the high-temperature properties of the structural materials which he offers and the purchaser is to blame for failing to recognize that the conditions under which metallic high-temperature equipment is used are far more severe than those to which the usual metallic structure is subjected, and that to insure satisfactory performance under these more rigid requirements of metallic units or structures for use at high or varying temperatures is at least as difficult as to construct an office building or to manufacture production machinery, neither of which would be entrusted to a purchasing agent, chemist or master-mechanic.

The more complete recognition of fundamental principles involved, and the growing accumulation of practical workable data, combined with the truly remarkable properties available in alloys of the present time are making for a large number of operations of a degree of precision and intricacy heretofore thought impossible and will in time result in the continuous automatic, accurately-controlled operation of present-time intermittent processes, and make possible the development of new processes not feasible at the time of this writing.

DETERIORATION OF SOME METALS IN HOT, REDUCING AMMONIA GASES[1]

By J. S. Vanick[2]

Introduction

Progress in some of the chemical industries has been marking time waiting for the development of materials suitable for service in certain of the reducing gases. Within the past few years the publication of a number of papers dealing with various phases of the action of reducing gases upon metals indicated that the industrial demand was inspiring the actual promotion of such work.

In a broad classification gases may be designated as oxidizing, reducing and neutral or inert. Oxygen and hydrogen are the principal agents of oxidation and reduction while their molecular combinations with other elements allow other reactions such as carbonization or sulfurization. Gases such as O_2, CO_2, SO_2, NO, etc., are considered oxidizing chiefly because they are compelled, somewhere along the temperature scale, to form an oxide of the pure metal with which they come in contact. Very few of the hydrogen compounds of the metals are known; hence gases such as H_2, CH_4, NH_3, H_2S, SiH_4, etc., receive their designation as reducing gases because they are able to deoxidize the metallic oxide. There is some evidence to indicate that pure hydrogen in contact with most of the pure common metals may be considered inert and to some extent, the same is true of pure nitrogen.

Most of the destruction of the normal properties of metals occurs from contact with a reducing gas of which hydrogen forms a part of the molecule. The splitting of the molecule into its components, one of which may be hydrogen, permits that element to penetrate the metallic surface and proceed on its own free course or combine with available elements in the interior, such as oxygen or carbon. Hydrogen is one of the most fluid of the gases and few if any metals are impervious to its passage at elevated temperatures.

Unlike oxidation, a visible surface film is not formed to protect the interior from a progressive infiltration of the gas. In general, the temperature, pressure and concentration of the gas, which in industrial practice is usually in circulation or motion, determines the character of its action. In such practice, some form of inequilibrium is usually manifest. More strictly speaking, the gas-metal reactions are usually reversible and the direction of the reactions between the solid and gaseous phases depends upon the relation of the phase components to equilibrium.

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[1] Published by permission of the Director, Fixed Nitrogen Research Laboratory, Department of Agriculture, Washington, D. C.

[2] Formerly Research Operator in Metallurgy, Fixed Nitrogen Research Laboratory.

In the attack of ammonia and its constituent gases upon metals an excellent opportunity is presented for observing the influence of a hydrogen-bearing reducing gas upon metals. Dry ammonia dissociates into its component gases at relatively low temperatures but remains reducing in its action regardless of the degree of dissociation. The reverse reaction, the synthesis of ammonia from its constituent gases, nitrogen and hydrogen may be accomplished under suitable conditions of temperature or temperature and pressure. These reactions are commonly described as "cracking" and synthesizing, depending upon whether the equilibrium concentration of ammonia for the physical conditions applied is approached from above or below, respectively. The only difference in the effects upon metals of the direction of reaction occurs in the rate at which metal is destroyed when in contact with the gases. In the dissociation, the "cracked" molecule of ammonia is separated into four atoms, each of which is spontaneously seeking some combination more stable for the instant than the former molecular ammonia association. In the case of iron or steel, for example, the optimum conditions for ammonia "cracking" are accompanied by the formation of nitrides within the temperature ranges wherein those nitrides are quite stable. During the ammonia synthesis, evidence of the formation of nitrides is not discernible, microscopically at least, and the direction of the reaction would require their immediate decomposition. Whether the reaction proceeds in one direction or the other, hydrogen is an important constituent of the mixture. For service at a temperature of about 500° C., pressure of 1500 lb. and contact with the ammonia gas mixtures, the metal should show a superior resistance to corrosion, deterioration and disintegration. Apparently none of the metals which were exposed to the gas mixture were corroded in the sense in which corrosion is understood. Corrosion carries with it a mental picture of surface destruction that fails to convey the impression of possible internal decay. Deterioration more aptly describes the effect which was produced within most metals. It implies a lessening in the quality of metal such as a reduction in its normal physical properties without a perceptible change in external appearance. It will be used here particularly with reference to degeneracy in physical properties. Disintegration implies the division of an assembly of units into its individuals. It might be used to express the separation of atoms or molecules of a metallic grain into its individuals or the separation of a granular aggregate into grains or fragments. In this description it shall be generally used in the latter sense.

PROCEDURE AND RESULTS

In the tests at the Fixed Nitrogen Laboratory, exposures to mixtures of ammonia gases were made for as long as six months under different conditions. Many miscellaneous tests were made for shorter intervals, the unsuitability of the material for practical service (usually because of porosity or lack of machineability) limiting the time or attention devoted to the test. In some cases, only a small supply of the sampled material was available and investigation was limited to microscopic inspections of sectioned specimens that had been exposed. The original method of testing consisted of exposing a few specimens suspended on a nichrome rod to a current of gas under pressure and high temperature. One of the group of specimens was removed at specific intervals such as one week, two weeks, one month, two months, four months, and six months, and examined. In a few instances tests are included which were made with the gas under pressure and

TABLE I.—COMPOSITION OF MATERIALS.

All values are expressed in per cent.

	Material	C	Mn	P	S	Si	Ni	Cr	Cu	Fe	Remarks	Source
No. 1, 2, 3	Commercial Copper											
No. 4...	Boron-deoxidized Copper........	....	....	....	....	....	....	....	....	....	Oxygen 0.0063 per cent. Boron not detected spectroscopically.	General Electric Co.[1]
No. 5....	Copper reduced and fused in hydrogen	....	....	....	....	....	....	....	....	....	....	Cleveland Wire Division, General Electric Co.[2]
No. 6....	....	0.06	0.23	....	....	0.21	98.7	....	0.15	0.50		
No. 7....	....	0.25	2.10	....	....	0.20	65.8	....	29.2	2.30		
No. 8....	....	0.19	1.05	0.022	0.031	0.16	36.3					
No. 9....	....	....	0.70	....	....	0.20	80.0	15.0	0.20	....	Approximate analysis	
No. 10...	....	0.40	0.82	0.020	0.018	3.22	15.3	16.0	....	....	....	Crucible Steel Co.[3]
No. 11...	....	0.02	0.01	0.007	0.032	0.006						
No. 12, 13	....	0.10	....	....	....	....	....	....	....	....	Approximate analysis	
No. 14[a]..	....	....	....	....	....	....	....	....	....	....	....	The Calorizing Co.[4]
No. 15[b]..	....	....	....	....	....	....	....	....	....	....	....	The Calorizing Co.[4]

[a] For composition, see "Calite—A New Heat-Resisting Alloy," by G. R. Brophy, Am. Soc. Steel Treating, February, 1922, Vol. 2, p. 384.

[b] For composition, see "Calorizing as a Protection for Metals," *Iron Trade Review*, January 27, 1921.

[1] Courtesy of Mr. T. S. Fuller, Metallurgist.

[2] Courtesy of Messrs. B. L. Benbow, Manager, and W. P. Sykes, Metallurgist.

[3] Courtesy of Mr. I. N. Beatty, Baltimore Sales Manager.

[4] Courtesy of Mr. F. D. Rice.

TABLE II.—SUMMARY OF MATERIAL USED AND CONDITIONS AND DURATION OF TESTS.

	Material	Form	Ammonia Atmosphere	Temperature, deg. Cent.	Pressure, lb. per sq. in.	Initial Stress, lb. per sq. in.	Time	Results
No. 1	Copper	Rod	Decomposing	400	none	none	4 months	$\frac{1}{8}$-in. rod, intergranularly fissured. Grains perforated and disintegrated to the center.
No. 2	Copper	Tube	Decomposing	140–600	1500	none	6 days	Wall 0.15 in. thick, riddled with a network of voids and fissures. Maximum deterioration occurs at contact of gas with catalyst, notwithstanding lower temperature at the contact zone.
No. 3	Copper	Rod	Synthesizing	500	1500	none	6 months	Minute fissures developed during a one week exposure. Fissures broadened after 2 months and continued so to end of six months' exposure.
No. 4	Boron-deoxidized Copper	Rod	Decomposing	100-700	none	none	1 day	Voiding appeared after 24 hours at 400° C. This was accompanied by grain growth at this temperature. Same features were more distinct at higher temperature exposures.
		Rod	Synthesizing	500	1500	none	1 month	Voiding and pitting observed after 2 weeks' exposure. Fissuring almost eliminated in so far as microscopic inspection permitted its detection.
No. 5	Hydrogen reduced Copper	Rod	Synthesizing	500	1500	none	6 months	Initially loose-grained or fissured. No intensification of this condition during 6 months' exposure.
No. 6	Nickel	Tube	Synthesizing	500	1500	4000	11 days	Failure of 9.0-mm. wall by intergranular fissuring in 256 hours.
		Rod	Synthesizing	500	1500	none	6 months	Penetration of 4.5-mm. wall in 2 weeks.
No. 7	Monel	Tube	Synthesizing	500	1500	4000	28 hours	Failure of 9.0-mm. wall by intergranular fissuring.
		Rod	Synthesizing	500	1500	none	6 months	Penetration of 4.5-mm. wall in 2 weeks.
		Rod	Synthesizing	690	none	none	4 months	Swollen to a loose, fibered incoherent mass.
No. 8	Invar, 30 per cent Ni-Fe	Rod	Synthesizing	500	1500	none	6 months	Pits and fissures permeate 4.5-mm. of wall after 2 weeks' exposure. Tensile properties indicate an appreciable coherence remaining.
No. 9	Nickel-Chromium	Rod	Synthesizing	500	1500	none	6 months	Fissures penetrate 4.5-mm. of wall, but are of the thickened type, suggesting a replacement. Retains an appreciable ductility.
No. 10	Fe-Ni-Cr-Si	Rod	Synthesizing	500	1500	none	6 months	Darkened, partially perforated skin, 0.20 mm. deep after 6 months' exposure.
No. 11	Ingot Iron	Tube	Synthesizing	500	1500	4000	13 days	Failure by intergranular fissuring of 4.5-mm. wall in 313 hours.
		Rod	Synthesizing	500	1500	none	6 months	Intermittent fissures penetrate 4.5-mm. after 2 weeks; become continuous and widened with increasing time.
No. 12	Steel Low Carbon	Tube	Synthesizing	500	4500	......	20 days	Failed by longitudinal fissures, after 20 days. Interior decaburized and interwoven with fissures.
No. 13	Steel Low Carbon	Tube	Synthesizing	500	1500	......	30 hours	0.25-in. wall appears but slightly affected after 30 hours. Loss in tensile properties approximates 3 per cent.
No. 14	Fe-Ni-Al	Rod	Synthesizing	500	1500	none	6 months	No change microscopically visible after 6 months' exposure.
No. 15	Aluminum-coated Iron	Tube	Synthesizing	500	1500	none	14 days	No change microscopically visible.
No. 16	Aluminum-coated Iron	Tube	Decomposing	200–550	none	none	(?)	Continues in service, uninspected after 6 months.

temperature acting upon a metal container or bomb. Such tests, in view of the tensile strength necessary, were made only on nickel, monel and iron.[1] These bomb exposures were more thoroughly inspected. Where temperature, pressure and concentration of ammonia are not mentioned, 500° C., 1500 lb. per sq. in. pressure and 8.0 per cent ammonia in a 3 to 1 hydrogen to nitrogen mixture, were used. Under these conditions the gas mixture was slightly under the ammonia equilibrium value for synthesizing, with respect to ammonia. A summary of the composition of the materials and the results of exposures to the gas mixtures is given in Tables I and II.

DETAILS OF THE DETERIORATION

A. COPPER AND A FEW OF ITS MODIFICATIONS

(*a*) *Commercial Copper.*

The deterioration of copper and certain copper alloys by intergranular fissuring in reducing gases is quite well known. Precautions are taken in the industries to avoid undue exposure of copper and its alloys during processing. Heyn's[2] explanation of the reduction of the oxide accompanied by the formation of steam has been repeatedly confirmed. Pilling[3] and Moore and Beckinsale,[4] in separate papers, have described the effect of hydrogen upon copper for shorter exposures at slightly higher temperatures. In exposures to decomposing or synthesizing ammonia, the action was fundamentally similar, and little can be added other than an amplification of certain details. An 0.125-in. rod in a current of "cracking" ammonia at 400° C., when removed after 4 months' service as an electric lead wire, was swollen to 0.165 in. in diameter and found interwoven to the core with intergranular fissures which decreased in coarseness from surface to center. In the cross-section an outer shell of large grains enveloped a fine-grained circumferential band which in turn enveloped a fissured but more normal-grained core. This unusual structure suggested the following sequence of events in its development:

1. Penetration;
2. Deoxidation accompanied by fissuring;
3. Grain fragmentation accompanied by recrystallization;
4. Grain growth.

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[1] Part of a larger experimental program which included tests of a comprehensive group of alloy steels. The results of the work upon the steels are now being compiled.

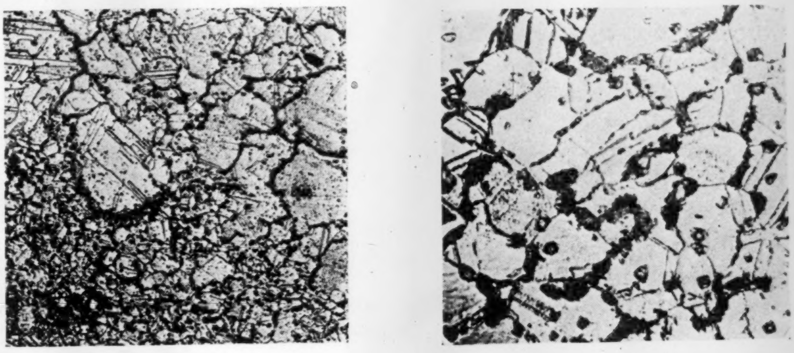
[2] E. Heyn, "Copper and Hydrogen," *The Metallographist*, Vol. VI, p. 39 (1903).

[3] N. B. Pilling, "The Action of Reducing Gases on Hot Solid Copper, *Transactions*, Am. Inst. Mining and Metallurgical Engrs., p. 1567 (1918).

[4] H. Moore and S. Beckinsale, "The Action of Reducing Gases on Heated Copper," *Journal*, Inst. of Metals, Vol. XXV, No. 1, p. 219.

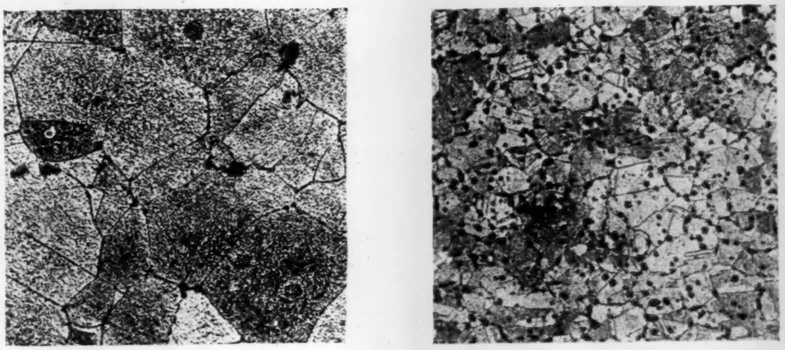
Examples of the normal-grained core area and coarse plus fine-grained enveloping area appear in Figs. 1 (*a*) and 1 (*b*).

In an 18-in. length of seamless copper tubing, operating as a catalyst well in the form in which it is sketched in Fig. 2, six days' service had riddled the 0.15-in. wall with a network of voids and fissures. A temperature gradient of about 400° C. existed over the length of tubing. The plotted temperature gradient had the form of a round-bottomed V-shaped curve with its apex 9 in. from the top of the well at 600° C., and its ends at 200° C. Although the maximum



(*a*) Copper rod ⅛ in. in diameter after 4 months' contact with decomposing ammonia at 400° C.; junction of coarse-grained outer shell within inner, broken grains. (× 100.)

(*b*) Same as (*a*); fissured core shows less grain fragmentation. (× 500.)



(*c*) Copper (reduced and fused in hydrogen) after 30 days in synthesizing ammonia at 500° C. and1500 lb. Initially loose grained, shows no additional deterioration in 6 months' exposure. (× 100.)

(*d*) Copper tube in contact with catalyst and synthesizing mixture at about 500° C. (× 100.)

FIG. 1.—Structures in Copper after Exposure to Ammonia Gas.

temperature was reached in the upper third of the tube, and the concentration of ammonia formed after the gas left the bottom of the tube was less than 0.1 per cent, the most deterioration occurred at about the middle of the tube, in the region of the initial contact of the gas with the catalyst. This is significant in view of the less vigorous action of the slightly greater hydrogen concentration of the incoming gas at the higher temperature. The tube showed voiding and fissuring over its entire length, the modifications of this effect differing only in degree. Apparently the lower temperature and very small ammonia concentration was able to do more damage than a higher temperature and no ammonia.

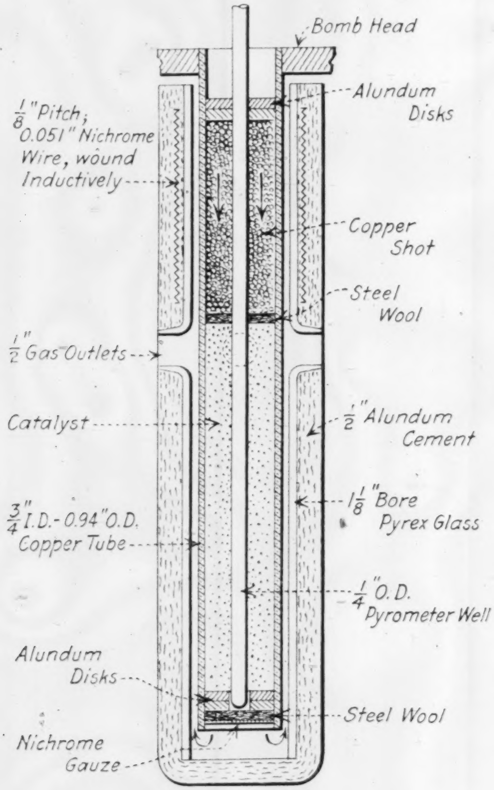

Bomb Head
Alundum Disks
$\frac{1}{8}$" Pitch; 0.051" Nichrome Wire, wound Inductively
Copper Shot
Steel Wool
$\frac{1}{2}$" Gas Outlets
Catalyst
$\frac{1}{2}$" Alundum Cement
$1\frac{1}{8}$" Bore Pyrex Glass
$\frac{3}{4}$" I.D.-0.94" O.D. Copper Tube
$\frac{1}{4}$" O.D. Pyrometer Well
Alundum Disks
Steel Wool
Nichrome Gauze

FIG. 2.—Copper Tube in Catalyst Well Service.
Greatest deterioration occurs at initial contact of gas with catalyst

Corrosion specimens (19.5 mm. in outside diameter with a 1.5-mm. bore) of commercial copper which were exposed for a total period of six months to a synthesizing mixture of gases at a temperature of

500° C. and a pressure of 1500 lb. were interwoven with minute fissures throughout the wall within a one-week exposure. The fissures increased in coarseness with time, becoming quite broad and open after a two-months' exposure. Continued exposure through the six months' interval added little to the already thorough destruction. The perforated appearance of the structure would lead to the expectation of brittleness. Commercial copper after exposure to the gas would always break when subjected to a slight bend.

(*b*) *Boron-Deoxidized Copper.*

Ruder[1] has described the resistance of boron-deoxidized copper to reducing gases. If the oxide of copper is responsible for the fissuring and voiding, obviously the deoxidation, to be effective, should be complete. Boron-deoxidized copper exposed in one series of tests to the synthesizing reaction and in another series to the decomposing reaction, sustained similar deterioration in each. A very slight fissuring in the very coarse grains indicated that deoxidation had not been complete, and an analysis for oxygen yielded 0.0063 per cent, roughly ten per cent of the quantity usually present in commercial copper. Analyses to the degree of sensitivity of the spectroscope failed to reveal the presence of boron. In the twenty-four hour exposures to the "cracking" reaction in 100° steps, up to 700° C., voiding was first discernible in the specimen representing the 400° C. exposure. Evidence of recrystallization first appeared in the same specimen. It seems that recrystallization was encouraged by the presence of the gas which, again, probably acted in the sequence previously mentioned.

(*c*) *Copper Reduced and Fused in Hydrogen.*

In an attempt to secure copper free of oxygen, a supply of copper which had been precipitated as hydroxide, then dried, baked and fused under hydrogen was prepared. The fusion was allowed to cool in the crucible. The volume of hydrogen dissolved during the fusion must have been appreciable because the ingot was piped and porous. Hothersall and Rhead[2] reported that hydrogen-treated copper was liable to pipe badly on casting unless a comparatively large amount of arsenic was present. Arsenic is itself a reducing agent at liquid copper temperatures and its mission in preventing the "blowing" of solidifying fusions is not entirely clear. Whether its influence is exerted in repelling the infiltration of oxygen, in forming a soluble hydrogen arsenic compound, in reducing the volume of dissolved gas by forming a volatile hydrogen-arsenic compound or an insoluble or volatile compound, remains to be worked out. Perhaps other deoxidizing additions would also prevent the "blowing." On account of the "blowing" during solidification, the hydrogen-fused copper was initially porous. In an exposure over six months no intensification of the original porosity was observable and no change in the appearance of the individual grains was detected.

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[1] W. E. Ruder, "The Brittleness of Annealed Copper," *Journal*, Franklin Inst., Vol. CLXXXI, p. 859 (1916); also W. H. Bassett, Discussion, *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. LX, p. 337.

[2] Hothersall and Rhead, *Journal*, Inst. of Metals, Vol. XXIII, No. 1, p. 367 (1920).

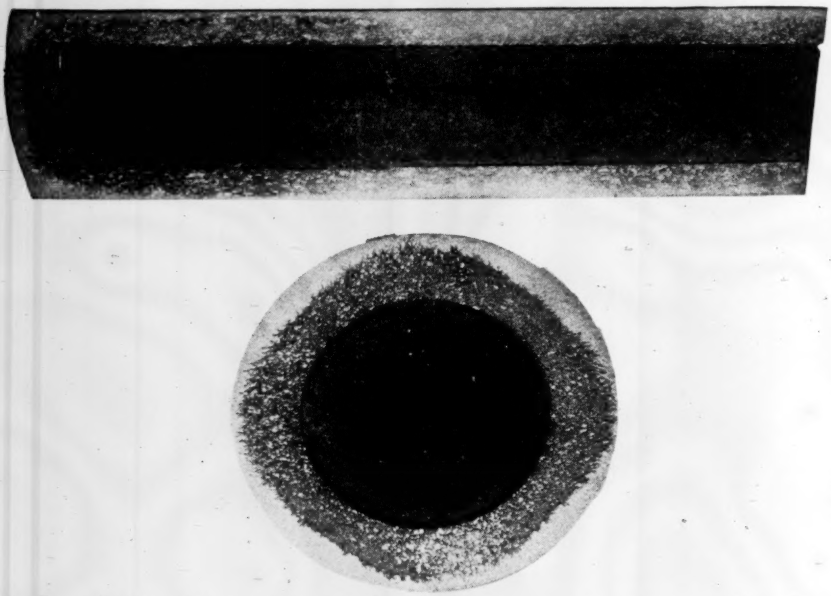

FIG. 3.—Two-inch Nickel Cylinder after Holding Synthesizing Mixture of N_2+H_2+ 8.0-per cent. NH_3 for 256 hours at 500° C. and 1500 lb. per sq. in pressure.

Deep etching reveals the position of coarse fissures at the time of failure. (Dark core is lead, cast into cylinder to preserve the edges during sectioning and grinding.)

The two views are of the same object shown to two different reductions. The original photograph from which these reproductions were made shows the section $2\frac{1}{16}$ in in diameter.

Fig. 1 (*c*) illustrates the microstructure typical of this material either before or after exposure.

B. NICKEL AND SOME OF ITS ALLOYS

Nickel and some of its alloys are well known for their strength and resistance to corrosion at elevated temperatures. This fact prompted a test of grade A nickel, monel metal, nickel-iron, nichrome, and nickel-chromium-iron. Pressure bombs were built only of nickel and monel metal. Corrosion specimens of all of the alloys were exposed for six months in the synthetic mixture at 500° C. and 1500 lb.

pressure. Tension test specimens of most of them were available and pairs of these were tested before and after exposure. With the exception of the nickel-chromium-iron, all of the alloys containing nickel yielded to intergranular fissuring, which, as in copper, destroyed much of the coherence between the metallic grains without disintegrating or corroding them. The nickel-chromium-iron alloy after a six months' exposure, showed only a thin discolored ring 0.20 mm. deep.

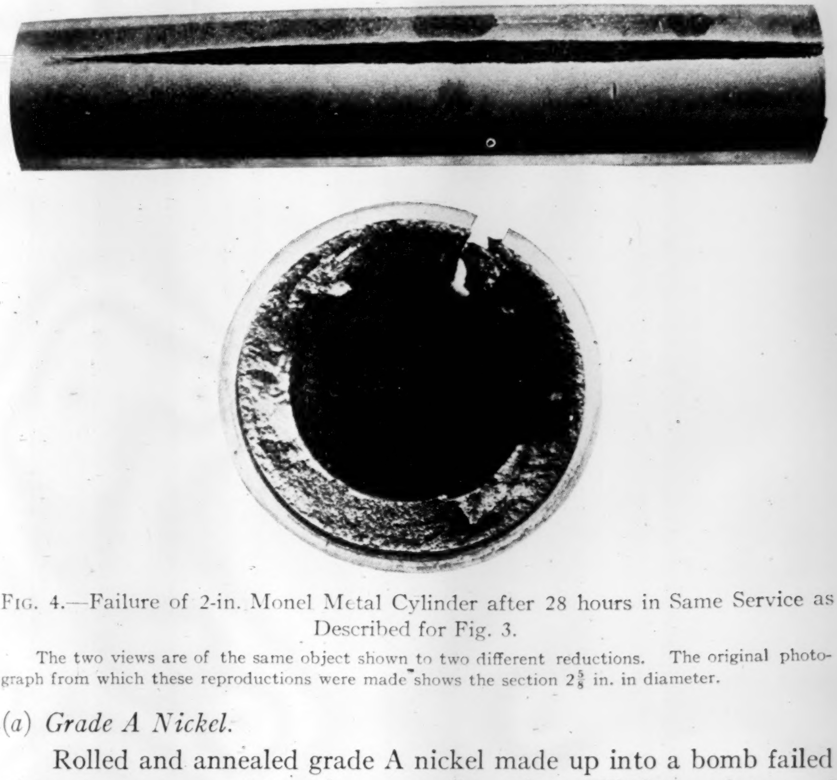

FIG. 4.—Failure of 2-in. Monel Metal Cylinder after 28 hours in Same Service as Described for Fig. 3.

The two views are of the same object shown to two different reductions. The original photograph from which these reproductions were made shows the section $2\frac{5}{8}$ in. in diameter.

(*a*) *Grade A Nickel.*

Rolled and annealed grade A nickel made up into a bomb failed after an exposure of 256 hours to the sub-equilibrium mixture of nitrogen, hydrogen and ammonia, at 500° C. and 1500 lb. pressure, by fissuring that permitted a rapid escape of gas. The gas had worked its way through the metal and succeeded in opening fissures similar to those shown in Fig. 6 (*a*). A deep etching of cross-sections of the bomb revealed the depth of deterioration. In places the fissures had passed through the entire wall. Fig. 3 illustrates the position of the coarsely fissured zone. Tension tests of specimens of 0.2 sq. in. sectional area cut from the bomb walls, though breaking in a progressive rupture caused by the lack of coherence and dependent ductility of the affected zone, roughly confirmed the degree of destruction. Tests of standard tension test specimens which were exposed unstressed to the gas within the bomb, are also included in the following:

Specimen No.	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Remarks
B. W. 1	20 190	.....	2.0	Irregular break	Bomb wall
B. W. 2	14 990	.....	2.5		Bomb wall
T. S. 1	58 838	35 048	12.5	Fillet break	Tension specimen exposed to gas
T. S. 2	.....	Broke in threaded section			Tension specimen exposed to gas
O. 1	75 850	21 270	52.0	76.2	Original specimen
O. 2	76 750	27 180	52.0	71.0	Original specimen

A comparison of the microstructure of the original with the bomb wall material revealed a distinct fissuring and grain growth in the latter. Grain growth had apparently been promoted by the applied stresses in the fissured zone. No evidence of grain growth in the same material appeared in the tension and corrosion specimens which were exposed unstressed for as long as 6 months. The type of deterioration was similar in every case. Fissures penetrated the entire body of the corrosion specimens ($\frac{3}{8}$-in. wall) in a period of two weeks. Further exposure enlarged the fissures without additional evidence of destruction.

(*b*) *Monel Metal.*

Monel metal subjected to the same tests as the nickel revealed its susceptibility to the same form of deterioration at a more rapid rate. A monel metal bomb exploded after an exposure of 28 hours. Fig. 4 illustrates the type of failure. Etched cross-sections of the bomb showed that the gas had penetrated the wall, and tension tests confirmed these findings.

Specimen No.	Ultimate Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Remarks
B. W. 1	27 500[a]	.....	3.0	....	Bomb wall
B. W. 2	21 800	.....	4.5	....	Bomb wall
T. S. 1	25 550	Broke in fillet			Tension specimen exposed to gas
T. S. 2	25 060	Broke in fillet			Tension specimen exposed to gas
O. 1	85 300	36 200	47.0	63.4	Original specimen
O. 2	97 200	49 900	45.0	66.1	Original specimen

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[a] After specimens cracked through 80 per cent of the sectional area, the load was sustained by the thin, outer layer (unexposed).

The tension test values roughly measure the strength of the unaffected metal. The initial strength, averaging 91,000 lb. per sq. in., had decreased to 25,000 lb. per sq. in., the decrease signifying that roughly 70 per cent of the sectional area of the wall had been penetrated. The tests were not strictly true measures of the tensile properties because of the early failure of the corroded portion; the consequent eccentric loading of the remaining portion produced a tearing action as the rupture moved across the fibers. The mode of rupture obviously reduced the tensile strength.

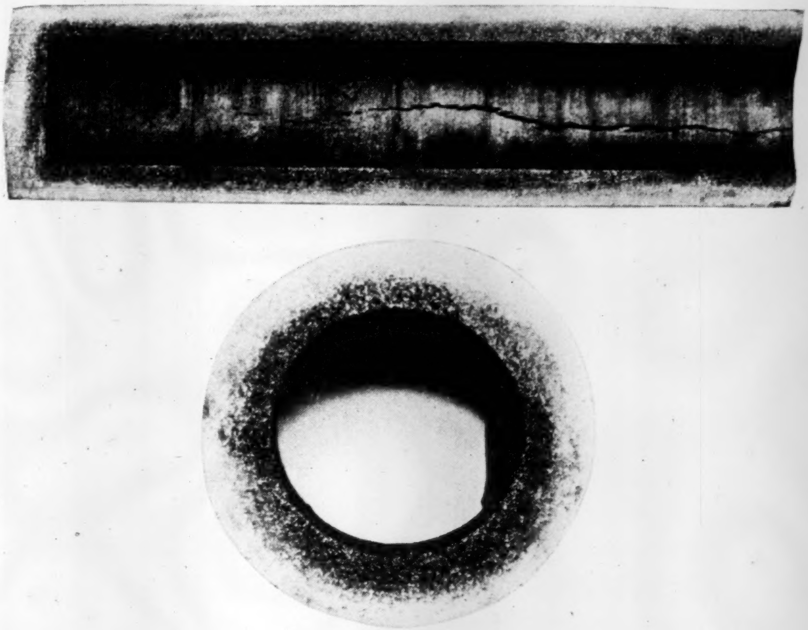
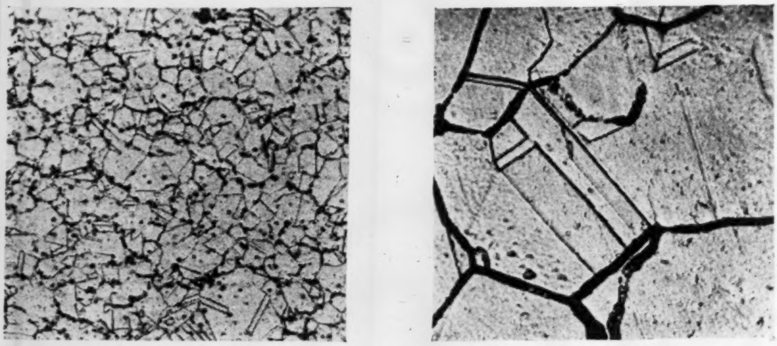


FIG. 5.—Failure by Longitudinal Fissuring in the 2-in. Ingot Iron Cylinder after 313 hours in the Same Service as Described for Fig. 3.

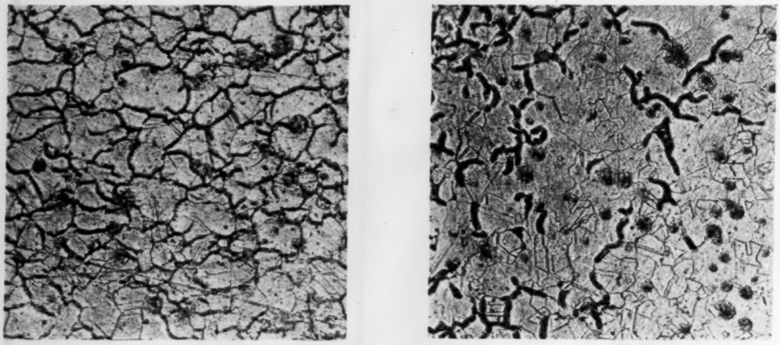
The two views are of the same object shown to two different reductions. The original photograph from which these reproductions were made shows the section $2\frac{1}{8}$ in. in diameter.

The average penetration into the bomb wall measured 7.7 mm. If the observed breaking load of 400 lb. is applied to this penetrated area and the observed breaking load of 4360 lb. to the unaffected area, values of 2470 and 114,500 lb. per sq. in. are obtained for the separate zones, respectively. These values, supplemented by the microscopic features, show that the strength of the fissured area was due solely to the residual coherence between contact surfaces of neighboring grains and to the interlocking of partially fissured gran-



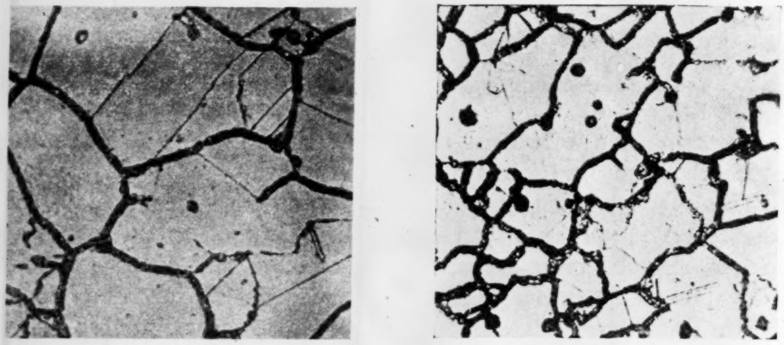
(*a*) Structure in nickel corrosion specimen after 30 days' exposure. Fissures which appear after 14 days' exposure are slightly enlarged in continuity and width. (× 100.)

(*b*) Intergranular fissures in the structures of the cylinder described in Fig. 3. (× 500.)



(*c*) Focused to emphasize network of fissures in the affected area of the monel metal cylinder described in Fig. 4. (× 100.)

(*d*) Terminus of zone described in (*c*) near outer, unaffected wall. (× 100.)



(*e*) Initially fine, intermittent fissures which are visible in monel, after 2 weeks' exposure, become as distinct as shown, after 4 months' exposure. (× 500.)

(*f*) Thick intergranular fillings in nickel-chromium suggest the formation of chromium nitrogen compounds. (×500.)

FIG. 6.—Structures in Nickel Alloys after Exposure to Ammonia Gas.

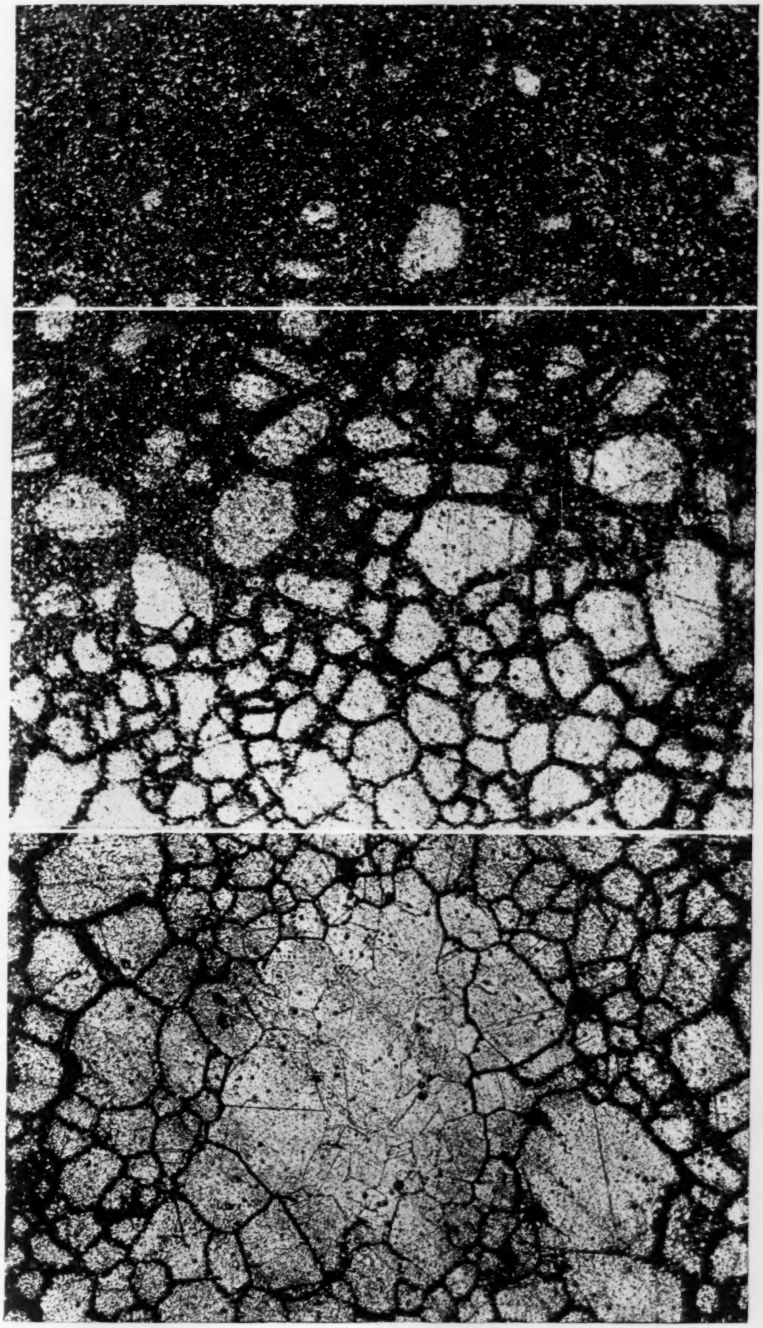


FIG. 7.—Full Cross-Section showing Disintegration of Monel Rod Embedded in the Catalyst where it was Exposed for 4 months to "Cracking" Ammonia at 690° C. (×100.)

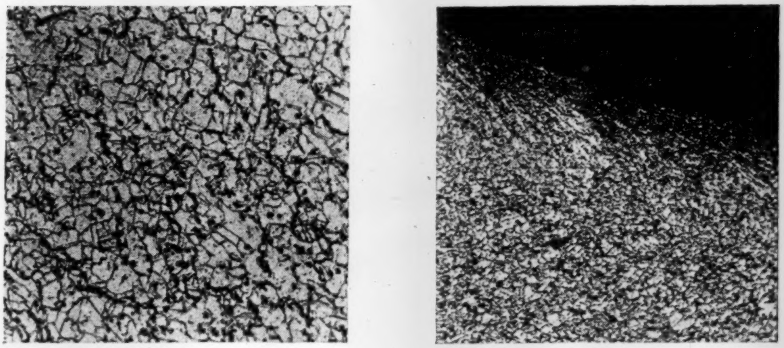
ular aggregates. Figs. 6 (*c*) and 6 (*d*) illustrate the type of intergranular fissuring occurring in the wall of the monel metal bomb. That the progress of the fissures through the metal was comparatively rapid is shown by the fact that the fissure traces are not closed through all of the intergranular paths in the disintegrated zone. Quite frequently a colony of grains is enveloped by the entering fissures without the isolation of the individuals in the colony. No evidence of grain growth appeared in the fissured zone. Grain growth may have been prevented by the lessened time of exposure.

The corrosion and tension test specimens which were exposed unstressed for six months showed the same type of deterioration. No evidence of grain growth was revealed within them. Fissures penetrated the 4.5-mm. wall of the corrosion specimens in two weeks. Continued exposure for the full six months failed to coarsen the fissuring or further the disintegration. The condition of the structure in one of these specimens after a long exposure is illustrated in Fig. 6 (*e*).

An interesting example of the effect upon metal of "cracking" ammonia was obtained by embedding a rod of monel metal in the "cracking" zone of a catalyst. The rod was exposed for a period of four months, at a temperature of 650 to 690° C. When examined, the 0.25-in. diameter rod had swollen to 0.35 in. and had burst along several longitudinal paths, which "laid open" the interior to the core. A fiberization of the metal had given it the texture of a loose-strand rope which lacked transverse coherence and could be readily crumbled in the fingers. Fig. 7 illustrates the appearance of a cross-section. Iron, copper, and nickel are subject to the same form of deterioration, in degree about in the order named, when embedded in the ammonia cracking zone of the catalyst bed. It is improbable that metals will be called upon for service in catalyst beds except as catalysts, in which case their chemical properties, chiefly, are of interest.

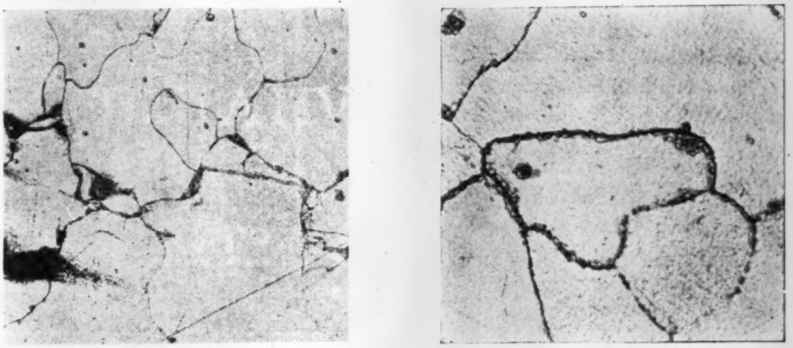
(*c*) *Nickel-Chromium, Nickel-Iron and Nickel-Chromium-Silicon-Iron.*

Groups of specimens of these alloys were exposed for a period of six months and periodically sampled. The nickel-iron and nickel-chromium showed intergranular fissures throughout their 4.50 mm. of wall after a two weeks' exposure. Further exposure served to coarsen the fissures and to indicate microscopically increased deterioration. Figs. 8 (*a*) and 8 (*b*) represent typical structures after an intermediate period of exposure to the gases. An item of interest occurs in a note describing the ductility of nickel-chromium rods which had been exposed under approximately similar conditions and which were capable of being bent several times through 180 deg.



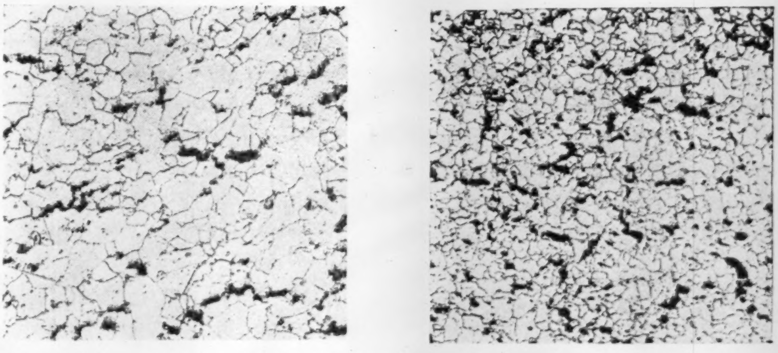
(*a*) Early formed pits and short fissures in nickel-iron have become connected into continuous fissures after 30 days' exposure. (× 100.)

(*b*) Narrow, darkened band along edge of iron-nickel-chromium-silicon alloy specimen indicated progress of probable chromium-nitrogen compound after 6 months' exposure. (× 100.)



(*c*) Intergranular fissures in the affected zone of the iron cylinder described in Fig. 5. (× 500.)

(*d*) Etching fluid exudations reveal the traces of very fine fissures in corrosion specimen of iron, after 30 days' exposure. (× 500.)



(*e*) and (*f*) Structures in low-carbon seamless steel tubes after 20 days in synthesizing ammonia gas at 4500 lb. pressure at 500° C. show decarburization and fissuring. (*e*) representing inner side of wall which was first attacked, shows grain growth. (× 100.)

FIG. 8.—Structures in Affected Zones of Materials Exposed to Synthesizing Ammonia Mixtures at 500° C. and 1500 lb. Pressure.

before failure. They retained appreciable tenacity in spite of microscopic indications of a thorough penetration of the gases. An explanation for this is offered, based upon the thickened appearance of the intergranular filling which suggests the formation of a chromium nitride that acts as a cementing material in the conglomerate of ductile nickel-chromium grains.

The nickel-iron alloy shows the usual loss in ductility in measurements of its extensibility although an appreciable coherence seems to be maintained in the fissured mass as the tensile strength values show. The results of tests upon companion specimens follow:

Specimen No.	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Remarks
T. S. 1.........	70 100	53 700	10.9	Broke in fillet	After exposure
T. S. 2.........	66 200	52 700	15.6	Broke in fillet	After exposure
[a].............	100 000	64 000	25.0	50.0	Initial condition

---

[a] Taken from U. S. Bureau of Standards *Circular No. 100*, on Nickel.

The iron-nickel-chromium-silicon alloy presented by far the best resistance to penetration of the gases and attendant deterioration. After a six months' exposure, a discoloration 0.20 mm. deep in the 4.50-mm. wall revealed the extent of the microscopically observable deterioration. The discoloration probably represents the zone within which a combination of nitrogen from the ammonia with the chromium of the iron-nickel-chromium solid solution occurred. A single tension test, made upon a tension test specimen which had been exposed to the gas mixture for six months, indicated a comparatively small loss in strength. The rupturing of the specimen in the grips of the testing machine suggested some embrittlement, although the gage-length portion of the specimen showed an appreciable extension. The tensile strength data are based on the standard 0.505-in. diameter, notwithstanding the fact that the rupture occurred through the head of the specimen. This single test would require confirmation for truer values. The microscopic evidence of the resistance of the alloy to the gases remains significant. The tensile data follow:

Specimen No.	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Remarks
T. S. 1..........	127 160	105 900	7.5	[a]	Exposed
Original.........	146 870	107 250	25.5	40.1	[b]

---

[a] Broke in specimen head.

[b] Approximate values of grade 2. From published data, *Transactions*, Am. Soc. Steel Treating, Vol. 1, p. 559 (1920).

C. IRON AND LOW-CARBON STEEL

A few examples of failures in low-carbon steel and iron show that these metals are subject to the usual intergranular deterioration when exposed to either the cracking or synthesizing mixtures. The progress of the gases into the metal is readily observed in steels of which an extensive series has been tested.[1]

Failures of low-carbon steel tubes were responsible for originally drawing attention to the metal deterioration problem. Examples typical of deterioration in the cracking mixture at atmospheric pressure have been described elsewhere.[2] In the synthesizing mixture the deoxidation, decarburization and application of stress due to the pressure, combine in hastening the deterioration by internal fissuring.

(*a*) *Ingot Iron.*

Under the usual conditions of test, namely 500° C., 8.0 per cent ammonia in nitrogen and hydrogen, and 1500 lb. pressure, an ingot iron bomb failed after an exposure of 313 hours. Fig. 5 illustrates the occurrence of a coarse fissure in the metal, and Fig. 8 (*c*) a typical condition within the structure. The occurrence of pits or voids along the grain boundaries mark the former position of evacuated slag inclosures and carbide pools that had been reduced upon the infiltration of the gases. In view of their strategic position, the influence of the decomposition of the intergranular impurities in promoting disintegration by opening the heat-weakened grain boundary contacts and expelling and spreading the decomposition products along the grain contacts, seems obvious. In the case of the bomb wall, the micro-features indicating the progress of the deterioration might be tabulated as follows:

FORM OF DETERIORATION	DEPTH, MM.	PERCENTAGE OF TOTAL WALL THICKNESS
Pitting	6.985	75.0
Segmented or intermittent fissures	5.065	54.5
Coarse fissures	2.250	24.2
Total fissured zone	8.315	89.2
Wall thickness	9.300	100.

The fissures obtaining in 90 per cent of the sectional area would account for much of the loss in tensile strength as well as the loss in ductility.

Tension tests upon bomb wall specimens and upon tension test specimens after six months' exposure follow:

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[1] The result of this work is in course of preparation and will shortly be available for publication.

[2] J. S. Vanick, "Deterioration of Steel and Wrought-Iron Tubes in Hot Gaseous Ammonia," *Transactions*, Am. Soc. Steel Treating, Vol. IV, No. 1, p. 62 (1923).

SPECIMEN NO.	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT	REMARKS
B. W. 1..........	15 670	......	6.0	[a]	Bomb wall
B. W. 2..........	15 824	14 560	7.0	[a]	Bomb wall
T. S. 1...........	27 650	15 500	6.2	[b]	Tension specimen exposed to gas
T. S. 2...........	25 450	15 050	7.3	[b]	Tension specimen exposed to gas
O. 1..............	42 200	24 700	49.0	77.0	Original specimen

---

[a] Reduced area could not be determined on account of the bent and serrated edge of the fracture.

[b] Broke in fillet.

The higher tensile properties shown for the solid unstressed tension test specimens suggest the greater difficulty and lessened thoroughness with which the gases penetrate the metal. Corrosion specimens (4.50-mm. wall) showed very fine fissures which extended throughout the body of the specimen after two weeks of exposure. Continued exposure extended the length of the fissures and their continuity from the exposed faces but failed to open them more widely. Fig. 8 (*d*) illustrates the delicate traces which marked the fissure positions in these specimens after as long as six months' exposure.

(*b*) *Low-Carbon Steel.*

Low-carbon steels, such as are used in the manufacture of seamless thick-walled tubes, are susceptible to the same form of deterioration as the ingot iron. For example, a tube with a wall 0.25 in. thick operating with a charge of catalyst in a synthesizing gas mixture at 450 to 500° C. and 1500 lb. per sq. in. pressure showed microscopically little evidence of deterioration after 30 hours of service. Tensile test data indicated a loss of approximately 3 per cent in all values for the exposed tube, as follows:

	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	ELONGATION IN 6 IN., PER CENT	REDUCTION OF AREA, PER CENT
Original tube...	50 600	34 000	47.0	27.0	62.4
Exposed.......	49 000	33 100	45.0	23.6	59.4

Tubing from the same lot used at three times the pressure (4500 lb. per sq. in.) and otherwise equal conditions failed by the usual longitudinal fissuring after an exposure of 20 days. Inspections of cross-sections revealed a fissured, decarburized interior, accompanied by evidence of grain growth along the inner, more highly stressed wall. Several other failures of this same type had been recorded for seamless steel tubing in similar conditions of service. In every case, the fissuring and decarburization were the most prominent microscopic features.

D. MISCELLANEOUS MATERIALS—FE-NI-AL AND ALUMINUM-COATED IRON

The iron-nickel-aluminum alloy was exposed for 6 months in the synthesizing mixture without showing microscopic evidence of deterioration. The occurrence of shrinkage cracks and casting defects in the cast alloy, and the frequent difficulty of obtaining gas-tight castings of any metal or alloy prevented further consideration of this material.

The aluminum-coated iron endured exposures up to 30 days without showing microscopic evidence of deterioration. The aversion to the coated iron, the outer layer of which like all coatings is susceptible to minute imperfections that might lead to failure, prevented the continuation of the exposure. From the inspections made, the material composing the coating, presumably an iron-aluminum alloy, showed promising indications of resisting deterioration. In ammonia "cracking" service, in which a few ounces of pressure are sufficient for operation, an aluminum-coated iron tube has been kept in service for longer than 6 months. This exposure still continues as no cause has arisen to require the disassembly of the apparatus. Ordinary, uncoated steel tubes ($\frac{1}{4}$-in. wall) have also given six months or more service in the low-pressure "cracking" operation.[1]

DISCUSSION

The attack of the hot reducing gas upon the metals appears to follow the same general course, namely, an intergranular fissuring which, in the synthesizing ammonia reaction, is usually unaccompanied by the formaton of detectable compounds. Of several factors contributing to the deterioration, the outstanding ones, in the order in which direct or circumstantial observations support their importance, are as follows:

1. The combination of impurities or alloying elements in the metal with the elements of the gas mixture.
2. The activity of hydrogen "cracked" from its compounds and the probable catalytic activity between the components of the gas mixture while it is in contact with metallic surfaces, regardless of the state of equilibrium between the gases.
3. Diffusivity and effusivity of hydrogen from confined intergranular cells leading to super-equilibrium in the gas mixture with respect to ammonia, with consequent formation and decomposition of nitrides.

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[1] J. S. Vanick, "Deterioration of Steel and Wrought-Iron Tubes in Hot Gaseous Ammonia," *Transactions*, Am. Soc. Steel Treating, Vol. IV, No. 1, p. 62 (1923).

Influence of Impurities.

The presence of elements, either as impurities or alloys that would react with the gas mixture, indicates one source of defection in the metals and outlines the probable course which deterioration would assume. As a simple example, oxygen in commercial copper would be expected to be rapidly reduced. Obviously, the quantity of oxygen available would exceed that compounded as oxide, to the extent of the solubility of the oxide or oxygen in the metal. The complete deoxidation by the infiltering gas would increase the porosity and accommodate by solution or absorption an appreciable gas content. In the case of copper, the formation of water vapor and its escape along the grain contacts, where the coherence of the granular aggregate that composes the metal is most feeble at the elevated temperature, would account for most of the fissuring. The lessened deterioration of the deoxidized copper lends support to this view. In copper, hydrogen alone is capable of producing the deterioration.

Nickel and iron contain small amounts of oxide, and possibly oxygen, which are reduced, as well as carbon that is removed during exposure.

Of greater significance than the voiding following the elimination of these impurities from the metallic matrix, is the probable promotion of intergranular fissuring attending the expulsion of the reaction products. In view of the modification of this effect in the deoxidized copper, an elimination of the removable impurities during the refining and casting should improve iron and nickel. The quantity of carbon and oxygen in nickel is slightly greater than that in iron, and the more rapid deterioration of the nickel is partly attributable to this cause.

There is no direct evidence, from the few short-time exposures to pure hydrogen that have been made upon nickel and iron, that an intergranular fissuring accompanies their deoxidation and decarburization. Most of the exposures have been of too short duration to permit the development of fissures. In the unstressed specimens, described above, two weeks in the gas mixture were required before fissures were detectable.

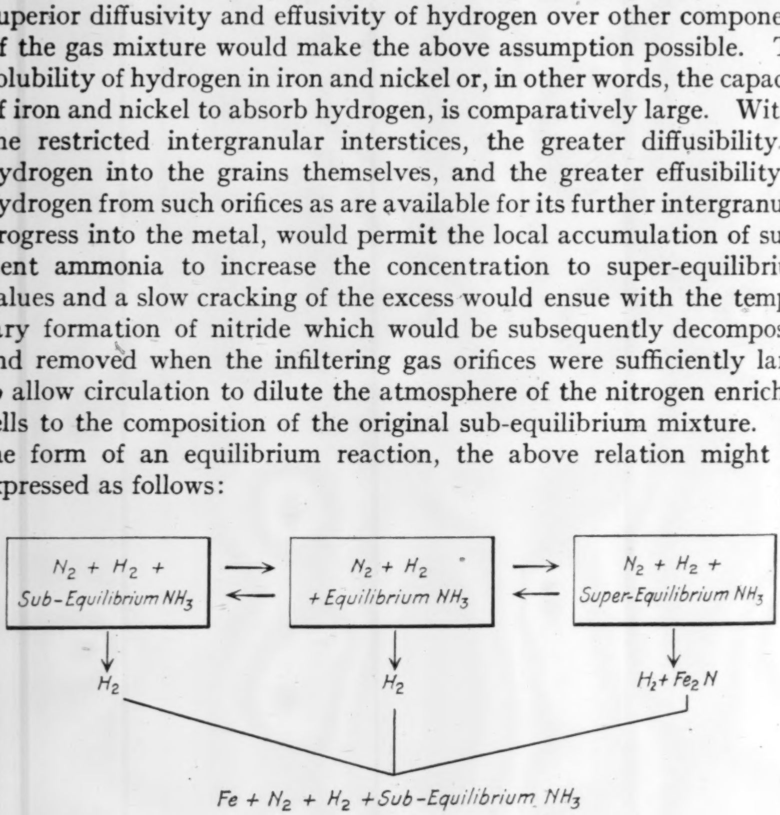
Molecular nitrogen at the temperatures of these exposures is similarly inert with respect to the metals considered. Another example of the influence of elements capable of forming stable compounds from the components of the gas mixture is presented in the case of chromium. Chromium apparently forms a stable or at least slowly decomposable compound in both the synthesizing and "cracking" reactions for the ammonia concentrations involved. In the case of the nickel-chromium alloy, a perceptible thickening of the grain boundary contacts suggests the formation of a chromium nitride which in view of the deep penetration apparently forms rapidly. In the case of the iron-nickel-chromium-silicon alloy, the very shallow infiltration suggests the formation of a nitride in an alloy initially quite impervious to the gas mixture. The sluggishness to diffusion or solution which chromium imparts to certain alloys is undoubtedly partly responsible for the retarded infiltration with attendant deterioration, in this latter metal. A corresponding resistance in the aluminum alloys indicates properties for them similar to those of chromium alloys.

Activity of Hydrogen.

The embrittlement of iron or steel during acid pickling or during contact with caustic solutions, where hydrogen is liberated, is well known, although the presence of fissures has not always been definitely established, nor has the mechanism of the reaction been thoroughly determined. The increased deterioration in the copper tube in the catalyst zone, described above, implies the activation of hydrogen under certain conditions. This activity, occurring in an ammonia concentration far below equilibrium, suggests the absorption of hydrogen with an accompanying swelling of the metallic grains, producing dis-registry at the grain contacts. Since this action is not observable where molecular hydrogen is used, the activation of the hydrogen upon filtering through the metal, or upon "cracking" the ammonia which is initially below equilibrium concentration, seems to be necessary. The "cracking" of sub-equilibrium ammonia would imply the action of a special force, such as catalysis, while the gas was in intimate contact with the permeable fabric of metal.

Super-equilibrium Ammonia with Alternate Formation and Decomposition of Nitrides.

Nitrides of iron, nickel and chromium are capable of being formed at this low temperature upon exposure to decomposing or "cracking" ammonia. In the synthesizing mixtures most of these nitrides are unstable and, with the possible exception of that of chromium, are rapidly decomposed. When iron, for example, is exposed to "cracking" ammonia a distinctly visible nitride is formed. By some investigators, the loosening of the grains, as well as the intercleavage precipitation of iron nitride, has been ascribed to the mechanical forcing apart of the grains and cleavages by the infiltering, depositing nitride. For the nitride to be deposited, ammonia must be "cracked," and the hydrogen liberated in the cracking must be expelled to allow the deposition to continue. In the synthesizing gas the iron nitrides are not detectable, as has been previously mentioned; yet the intergranular fissures are quite as distinctly developed. The monel metal rod, as another example, shows an extreme case of the disintegration of the grains of that alloy by "cracking" ammonia. The disintegration suggests, from its thoroughness, the spontaneous decomposition of an accompanying compound. To build up a super-equilibrium ammonia concentration in the synthetic sub-equilibrium mixture that was used in most of the exposures, it would be necessary to alter the pressure on the gas system or change its ammonia concentration. A pressure gradient altering the equilibrium relation is doubtful, especially in view of the fact that the corrosion specimens exposed under a "hydrostatic" (all-sided) pressure showed the same type and almost equal degree of deterioration as the pressure bombs exposed to a "one-sided" pressure. A more appealing explanation occurs in the possibility that hydrogen is withdrawn from the gas mixture that filters into the interstices between the grains, and the ammonia enriched atmosphere, by alternate nitrification and decomposition, enlarges, but chiefly prolongs, the intergranular passages. The superior diffusivity and effusivity of hydrogen over other components of the gas mixture would make the above assumption possible. The solubility of hydrogen in iron and nickel or, in other words, the capacity of iron and nickel to absorb hydrogen, is comparatively large. Within the restricted intergranular interstices, the greater diffusibility of hydrogen into the grains themselves, and the greater effusibility of hydrogen from such orifices as are available for its further intergranular progress into the metal, would permit the local accumulation of sufficient ammonia to increase the concentration to super-equilibrium values and a slow cracking of the excess would ensue with the temporary formation of nitride which would be subsequently decomposed and removed when the infiltering gas orifices were sufficiently large to allow circulation to dilute the atmosphere of the nitrogen enriched cells to the composition of the original sub-equilibrium mixture. In the form of an equilibrium reaction, the above relation might be expressed as follows:


N₂ + H₂ + Sub-Equilibrium NH₃
N₂ + H₂ + Equilibrium NH₃
N₂ + H₂ + Super-Equilibrium NH₃
H₂
H₂
H₂ + Fe₂ N
Fe + N₂ + H₂ + Sub-Equilibrium NH₃

The above hypothesis rests entirely upon the assumption that hydrogen filters out from the confined cells more rapidly than fresh gas can filter in and circulate about. To some extent, the intergranular cells or voids are partly developed during the earlier expulsion of hydrogen compounds of carbon and oxygen along the grain boundaries.

SUMMARY

Reducing gas mixtures of ammonia in nitrogen and hydrogen produce an intergranular fissuring in commercially pure iron, nickel, copper and some of their alloys. Exposures of samples in the form of corrosion specimens, tension test specimens or pressure bombs were made for as long as six months, to a synthesizing ammonia-gas mixture at a temperature of 500° C. and a pressure of 100 atmospheres. Short exposures were made to decomposing or "cracking" ammonia.

None of the metals except those exposed to "cracking" ammonia were corroded in the sense in which corrosion is usually understood, namely, as a surface attack accompanied by disintegration or the formation of chemical compounds. With corrosion so defined, nearly all of the materials tested resisted corrosion successfully, with some advantage in favor of the non-ferrous or non-ferrous alloy group. Nearly all of the materials suffered deterioration as measured by loss in mechanical properties such as tensile strength and ductility. For resistance to deterioration in a service requiring ability to sustain stress, as in heated bombs holding the gas mixtures under pressure, iron-base alloys of the type containing nickel, chromium or aluminum seem to offer most resistance.

In the synthesizing ammonia-gas mixture, most of the metals are subject to intergranular fissuring and voiding. This form of deterioration varies in rate and degree for the different materials. An intensification of the characteristic type of deterioration occurs in the catalyst zones during either "cracking" or synthesizing. Copper and monel rods exposed to cracking ammonia show evidence of a vigorous attack culminating in their disintegration. The influence of the direction of the reaction with respect to ammonia equilibrium, that is, whether synthesizing or cracking ammonia is active, is shown in the rate at which deterioration occurs, being more rapid in the cracking gas.

In the cracking gas, nitrides form which, with the removal of impurities and the accompanying large evolution of hydrogen, account for the disintegration and deterioration of affected metals. In the synthesizing gas, nitrides are unstable and consequently are not expected to contribute directly to the deterioration.

An explanation to account for the deterioration in the synthesizing mixtures is developed, as follows:

1. The removal of elements such as carbon or oxygen or their compounds encourages voiding and fissuring, while the presence of chromium, in forming more stable nitrides and retarding the diffusion and penetration of the gas, assists in resisting deterioration.

2. Fissuring is induced by dissolved hydrogen made soluble by activation from infiltration through the metal or by release from ammonia which is rendered unstable in contact with the catalytic metal surfaces.

3. The more rapid diffusion and effusion of hydrogen, in contrast to other gases of the mixture, permits an ammonia enrichment to the extent of developing a localized super-equilibrium, with the alternate formation and decomposition of nitrides as a result.

Acknowledgment.—In conclusion, an indebtedness is acknowledged to G. K. Burgess, director of the U. S. Bureau of Standards, for the use of his metallurgical laboratories; to W. W. Sveshnikoff, assistant physicist at the Bureau of Standards, for much help with the photography, and to C. H. Young, associate chemist at the Fixed Nitrogen Research Laboratory, for the supervision and maintenance of the exposure work.

SOME ENGINEERING APPLICATIONS OF HIGH-CHROMIUM-IRON ALLOYS

BY C. E. MACQUIGG[1]

During recent years an increasing interest has been displayed in alloys suitable for high temperature-pressure duty. This interest has been cumulative, as it were; the chemical engineer describing the service conditions to which apparatus will be subject, while the metallurgist, in striving to fulfill the requirements, will often perfect something just a little better, which in turn will open up new possibilities in chemical technology. Thus each advantage won makes further development more attractive.

High-temperature services generally involve requirements of permanence, such as resistance to oxidation or to the attack of other corroding agents—frequently both requisites simultaneously. High pressures require alloys with tensile properties which are not so materially reduced at advanced temperature as happens to be the case with plain carbon steels.

Among the desirable properties of alloys for high-temperature or corrosion-resistance work are: (1) good casting qualities, (2) machineability; (3) forgeability, (4) immunity to the attack of as many destructive agencies as possible and (5) strength. It is generally the case that no single alloy will meet all the above requirements to the desired extent. This emphasizes the fact to which attention has been frequently drawn, namely, that it is necessary to select material for the specific purpose in view and that failure to take into consideration all of the requirements of service may result in disappointment.

Because of their relative cheapness and their wide range of useful engineering properties, the alloys of iron and chromium deserve careful consideration. The alloy which it is proposed to discuss briefly here has been described elsewhere.[2] In the present paper, it may be interesting to consider the uses and limitations of an alloy with about 25 to 30 per cent of chromium and fractions of one per cent of silicon and manganese, the remainder largely iron. The carbon varies from about 0.1 to 3 per cent, depending on the properties desired.

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[1] Union Carbide and Carbon Research Laboratories, Long Island City, N. Y.

[2] "Some Commercial Alloys of Iron, Chromium and Carbon in the Higher Chromium Ranges," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. 69, p. 831 (1923).

CASTING QUALITIES

Excellent castings are readily made throughout the range of carbon contents. As explained later, the carbon has an important effect on casting quality, just as in the case of plain carbon steels. Where castings are required to be machineable with ease, carbon should not exceed 1.5 per cent, but much will depend on the size and rate of cooling as to where the line for easy machineability is to be drawn.

The general casting practice seems to follow that of steel more than that of cast iron. Shrinkage allowance is about $\frac{1}{4}$ in. per ft. Castings are sound and dense. The grain is dependent on the carbon content, as in steel, but is more susceptible to the rate of cooling than in the case of steel. The toughness of castings of these alloys is sufficient for the service conditions encountered in engineering practice. Small castings, as annealing boxes, require heavy sledging to cause breakage.

The effect of chromium in iron or steel, in general, is to reduce casting quality. By that is meant that the element, if present in any important amount, causes the melt to have a slightly thickened consistency which is increased with increase of chromium. With upwards of 20 per cent chromium and low carbon content, the tendency is for the alloy to have a somewhat "creamy" appearance as the metal runs from the spout. Carbon is an effective element for reducing this tendency. High chromium content in low-carbon alloys sometimes causes a greenish, leather-like oxide to form on metal that has been poured somewhat cold; this goes to the surface of the casting and causes a crinkly or folded appearance which, however, is not detrimental to the quality of the casting, since the folds are quite superficial. These folds disappear in the higher carbon ranges.

The ability to form sound castings is quite important in the case of alloys which are to be used as containers for fluids at high temperatures, as in the case of heat-treating baths, cyanide pots, etc. There is a tendency for most cast materials to develop enough porosity at high temperatures to produce pinholes and allow leakage which may even result in the destruction of the container. This tendency exists in cast iron, steel and other alloys. Thermal stresses engendered by alternate heating and cooling are quite severe, and articles which when first cast will present an apparently sound fracture may develop pinholes or fissures after varying lengths of service. This tendency is no doubt accelerated by the alternate heating up and freezing of the baths in the case of containers used in the heat-treating industry.

The defect seems to be inherent with cast alloys in general rather than with any particular combination, although ability to make sound castings will minimize the difficulty.

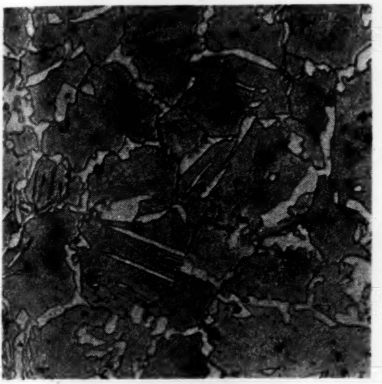

FIG. 1.—Cast Chromium-Iron Alloy, 0.10 per cent Carbon, 23.31 per cent Chromium (× 100).

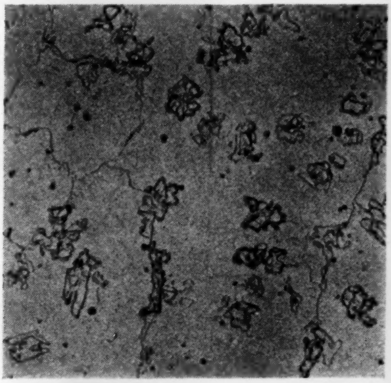

FIG. 2.—Forged Chromium-Iron Alloy, 0.16 per cent Carbon, 25.05 per cent Chromium (× 100).

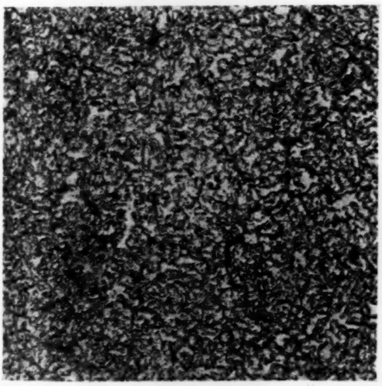

FIG. 3.—Cast Chromium-Iron Alloy, 1.18 per cent Carbon, 26.30 per cent Chromium (× 100).

FIG. 4.—Same Alloy as Fig. 3 (× 500). Note Details of Carbide and Solid Solution Groundmass.

MACHINEABILITY

While machineability is by no means a *sine qua non* for apparatus designed to resist oxidation, corrosion, etc., in practice it is found that the majority of applications require machineability, although in a large tonnage of castings the machineability requirements are lacking or may be met by grinding operations for facing, fitting, seating, etc.; in general, such cases represent isolated castings, for example, heat-treatment equipment. On the other hand, pieces intended for assembling into larger units, such as fittings for pumps, faced and drilled flanges, and equipment for the handling of liquids and gases, usually require machineability.

The hardness of the high-chromium alloys depends chiefly upon their carbon contents. Castings made in sand, as a rule, are easily machineable up to 1.5 per cent carbon and may be made machineable by suitable heat treatment with as high as 3 per cent carbon. Dismissing the rather intricate relationships between carbon and chromium as not pertinent to the present subject, the general physical properties of these alloys may be likened to those of the plain carbon-iron alloys ranging from the soft, malleable and ductile low-carbon to the very hard, high-carbon range. There is this difference, however, in that the very low-carbon alloys will be harder and stiffer than a simple steel of like carbon content, while at the other extreme the high-carbon alloys will be as hard or even harder than the white cast irons, but will possess a much greater toughness.

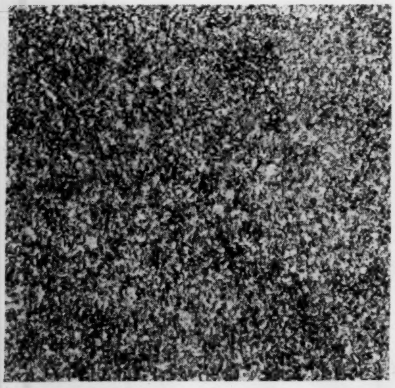

FIG. 5.—Same Alloy as Fig. 3 after Forging (× 100).

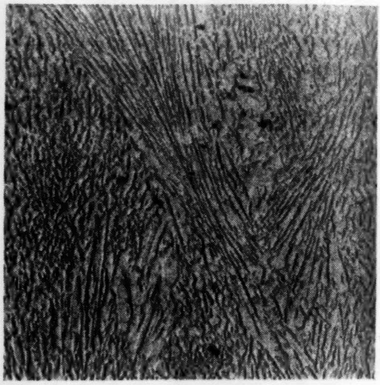

FIG. 6.—Representative Structure of Chromium-Iron Alloy, 2.88 per cent Carbon, 29.57 per cent Chromium (× 100).

Fig. 1 shows the cast microstructure of an alloy with 0.10 per cent carbon and 23.31 per cent chromium at 100 magnification. The structure consists of polygonal grains of solid solution. Such an alloy will have a Brinell hardness of 146 to 190, depending on treatment. Fig. 2 illustrates an alloy with 0.16 per cent carbon and 25.05 per cent chromium in the forged condition. Fig. 3 depicts the cast structure of an alloy with 1.18 per cent carbon and 26.36 per cent chromium. Fig. 4 is the same section at higher magnification to show the details of carbide and solid solution groundmass. Fig. 5 is the same alloy after forging. Fig. 6 shows a representative structure of an alloy with 2.88 per cent carbon and 29.57 per cent chromium. Such alloys consist of a groundmass of carbide - solid solution eutectic with scattered crystals of the excess carbide. The relative number and size of the latter will be a function of the carbon content of the alloy and to some extent its treatment. Such alloys will have Brinell hardness numbers ranging from 450 to 550 or 600 in the sand-cast condition and may be made materially harder by heat treatment. We have also succeeded in softening one of these high-carbon alloys from 532 to 321 Brinell, the latter being machineable.

WORKABILITY

Workability is obviously a desirable property in alloys used for their resistant qualities, and includes ability to be hot-hammered, pressed, and rolled. While castings suffice for many purposes, the same relationship between casting and forging holds as in the case of steel, namely, better physical properties in the worked material. Ability to form articles like plate, sheet, seamless or welded tubing, drop forgings, stampings, hot and cold-drawn ware, rods, and wire, obviously greatly increases the scope of usefulness of any alloy. Alloys with 20 to 30 per cent chromium have been commercially fabricated throughout the above category.

RESISTANCE TO ATTACK

Surface deterioration may be due to any one of several different agencies, or to combinations of one or more, namely, atmospheric corrosion, corrosion due to water, corrosion due to chemicals, destruction by abrasion, and failure due to deterioration at high temperatures. While the deterioration from abrasion is rather a special case, it is of considerable commercial importance, particularly in mining and in concentration of minerals. Deterioration at high temperature is largely due to oxidation, although there are other elements than oxygen which are quite destructive to certain metals at high temperatures. This is particularly true of sulfur and its oxides.

Plain iron-carbon-chromium alloys above 20 to 22 per cent chromium first attracted attention because of their peculiar oxidation resistance. This is probably their outstanding feature. The oxidation resistance of the high-chromium-iron alloys does not seem to depend upon any other factor to any such great extent as it depends upon the chromium content. Below about 20 per cent, while the alloys are very much more resistant to oxidation than ordinary steels, they are noticeably inferior in oxidation resistance to alloys above 20 per cent. Alloys with around 26 to 28 per cent chromium, when exposed to oxidizing atmospheres up to 1150° C. (2100° F.) or higher, remain good indefinitely. They accumulate a very thin, tough, adherent scale of oxide which is more like an enamel than a scale, and this appears to act as a protective coating against further surface deterioration; it also resists flaking off, even when subjected to extreme changes of temperature. Carbon monoxide and other reducing fumes and gases are without effect until very high temperatures are reached; however, above 1150 or 1200° C. (2100 or 2200° F.) such reducing atmospheres have a deteriorating effect on the alloys. At these temperatures, in the presence of carbon monoxide, actual oxidation takes place rather rapidly, and this has been explained by Charpy[1] as being due to the action of the CO on the chromium, forming Cr_2O_3 and C, some of the latter combining with the iron. So long as the atmosphere is oxidizing, the alloys seem to be safe nearly up to their melting points. These melting points are determined chiefly by the carbon content, varying from 1150° C. (2100° F.) for the very high-carbon combinations to 1430° C. (2600° F.) for the low-carbon alloys.

The carbon content does not materially affect the oxidation resistance. In other words, the presence of chromium not only increases the resistance of the solid solution to attack by the hot oxygen, but it also apparently makes the double carbides more resistant. With the very high-chromium alloys there is enough chromium to alter the chemical nature of the solid solution and of the carbide as well, rendering both more inert. It is an interesting speculation here as to whether the essential nature of wet corrosion and of dry oxidation is not the same. It seems that this may well be the case; that is, the surface of the metal at high temperatures is ionized so that the chemical nature of the oxidation is analogous to that which takes place by acid attack in solution at room temperature.

The subject of oxidation resistance immediately brings up the question of the most satisfactory way to determine this in the laboratory. The most obvious method is to prepare the metal in the form preferably of a cube by grinding the surface to a fair degree of fineness. A mirror reflecting surface is not necessary. The specimen is then subjected to the given temperature for at least 48 hours in an oxidizing atmosphere. This is readily obtained up to 1150 or 1200° C. in a wire-wound furnace where the atmosphere may be allowed free circulation. The scale is then removed from the test piece and the surface finished to about the same degree of fineness as before.

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[1] *Chemical Abstracts*, p. 1734, August 10, 1909, from *Comptes Rendus*, Vol. 148, p. 560.

This method is open to numerous objections. In the first place, the size of cube should always be about the same, in order to give the same ratio of surface to mass in all tests. Secondly, unless the compositions tested all have roughly the same rate of corrosion, the percentage losses are not strictly comparable, because of the variation in the ratio of surface to mass, due to more rapid oxidation of some of the test pieces than of others. Thirdly, the cleaning of the test piece necessarily introduces an element of error in that the metal will tend to pit to some extent, and even though this may be hardly appreciable when grinding down the test piece, some of the scale will be left on and some of the solid metal taken off. In the case of some metals it is possible to use chemical reagents which will attack the scale and not the metal. An example of such a reagent suitable for plain carbon steel is one part of water, one part of concentrated hydrochloric acid, to which is added 1 per cent by volume of formaldehyde.[1] In view of the shortcomings of laboratory tests, the most convincing results are always obtained in plant operation. Rough handling, thermal strains due to rapid heating and cooling, abrasion, and the other hazards of handling, may diminish the resistance of alloys which, under laboratory test conditions, apparently are satisfactory.

Sulfur and sulfur gases are without action up to 1000° C. on the high-chromium alloys substantially free from other metals, at least so far as laboratory tests can demonstrate. Tests have been made in moist mixtures of sulfur dioxide and oxygen for several hours at 1000° C., and after this treatment only light tarnishes appear on bright metal specimens. Sulfur vapor is apparently without action up to at least 1000° C. At 1100° C. pure sulfur causes slow deterioration by attacking the grain boundaries. The latter test, however, was made with a sulfur ore in which the attack on the metal was highly complicated by the presence of a chemically active slag. Laboratory results indicate that up to 1000° C., stills for sulfur or sulfur gases could probably be safely used. The action of sulfur compounds in crude oil is believed by many to be the cause of the failure of steel stills in the oil-cracking industry. Tests that have been under way for some time are expected to demonstrate the usefulness of the alloy for this application.

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[1] *Journal of Industrial and Engineering Chemistry*, p. 1159, December, 1920.

TABLE I.—TESTS OF LOW-CARBON ROLLED SHEET, ABOUT 27 PER CENT CHROMIUM, IN VARIOUS MEDIA.

Media	Strength of Solution, per cent	Temperature of Test, deg. Cent.	Duration of Test, hours	Penetration, in. per month × 100
Nitric Acid[1]	70	90	72	0.029
	70	120	72	0.24
	70	Room	168	None
	50	90	72	0.0094
	25	90	72	0.0059
	10	90	72	0.0019
	1	90	72	0.0027
Hydrochloric Acid[1]	36	Room	72	Dissolved
	25	Room	72	Dissolved
	10	Room	72	Dissolved
	1	Room	168	8.90
Sulfuric Acid[1]	95	Room	72	None
	95	90	72	0.99
	95	Room	168	0.0010
	50	Room	72	None
	50	90	72	Dissolved
	50	Room	168	0.0020
	25	Room	72	Dissolved
	10	Room	72	Dissolved
	1	Room	168	19.0
Glacial Acetic Acid[1]	..	90	72	2.30
	..	Room	72	None
	..	Room	168	None
Acetic Acid[1]	50	90	72	Dissolved
	50	Room	72	None
	50	Room	168	None
	25	Room	72	None
	25	Room	168	None
	10	90	72	7.8
	10	Room	72	None
	10	Room	168	None
Citric Acid[2]	85	Room	48	None
	85	85	48	None
	1	Room	48	None
	1	85	48	None
Phosphoric Acid[2]	85	Room	24	None
	85	100	24	0.22 per cent loss in weight on ½-in. cubes
	50	Room	24	None
	50	100	12	0.04 per cent loss in weight on ½-in. cubes
Sodium Hydroxide[1]	25	90	72	None
	10	90	72	0.0015
	1	90	72	0.0030

[1] Tests by Chemical Warfare Service.

[2] Tests by Union Carbide and Carbon Research Laboratories.

NOTE.—Tests in the Union Carbide and Carbon Research Laboratories with certain vegetables and fruits show that chemical action is negligible. Among those tested were apples, prepared mustard, tomatoes, rhubarb and tartaric, formic, malic, citric and oxalic acids in 1 per cent concentrations. These were all boiled in a chrome iron container for several hours and the extractions tested for iron and chromium.[a]

The desire to obtain a metal resistant to certain types of wet corrosion has led to experimental work on the high-chromium iron alloys by several independent investigators as well as by the laboratory of the Union Carbide and Carbon Corporation. From the very earliest development work it was apparent that practical immunity existed toward nitric acid. Later a request for information on resistance to fruit and vegetable acids led to further investigation. Table I shows the results of the tests made on fruit and vegetable acids; also a tabulation of results obtained in tests made by the Chemical Warfare Service at Edgewood Arsenal, to whom we are indebted for permission to publish the results. The tests were made on low-carbon rolled sheet with about 27 per cent chromium. Confirmatory tests have also been made by a firm of consulting chemical engineers. Mine water tests have been made under the auspices of the Carnegie Institute of Technology, the U. S. Bureau of Mines,[1] and the Coal Mine Advisory Board, on forged articles, and these showed acid mine-water resistance equaling the best in a field of about sixty competing alloys and metals. Other tests have proved the excellence of these rolled alloys in withstanding mine-water corrosion. This subject is of great industrial importance because of the large replacements of metal parts attributable to acid mine water.

Behavior of these alloys towards heat-treating baths has, in the main, been favorable, but conditions vary from plant to plant and it does not seem advisable to make a sweeping assertion where so many unknown factors are involved. The question of obtaining satisfactory metals for constructing pots, spouts, dies, etc., in the die-casting industry is a live one. Due to the corroding action of molten aluminum and the light alloys, this is a very severe service. A low-carbon forged alloy used for a spout in the die-casting process has given exceptionally long life.

Another use to which rolled and forged corrosion-resistant alloys would be peculiarly adapted is in parts subjected to corrosion by sea water. The requirement here is not only for resistance to corrosion but resistance to fouling by marine growths. The high-chromium alloy shows up favorably in the former respect, but so far as we are aware, no unprotected alloy has yet successfully resisted the tendency to become fouled, particularly in tropical or sub-tropical waters.

STRENGTH

The tensile properties of the alloys follow in a general way the same relationship to carbon as holds in steel and cast iron. Low-carbon alloys are soft and ductile. The elastic limit in this class varies from 45,000 to 70,000 lb. per sq. in. with corresponding tensile strengths of 75,000 to 90,000 lb. per sq. in. Ductility varies from zero to between 35 and 50 per cent for elongation and reduction of area. All of the above properties depend on the composition and heat treatment. With increase of carbon from 0.25 to 1 per cent or more, the strength and stiffness increase and tensile strengths run up to and well over 130,000 lb. per sq. in.

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[1] *Bulletins Nos. 4, 5 and 6,* Carnegie Institute of Technology, Pittsburgh.

Castings vary in tensile strength from 65,000 to 90,000 lb. per sq. in. with low ductility. As the carbon content increases, the hardness increases. With 2.75 per cent carbon the Brinell hardness of the sand-cast alloys may rise to 550 or 600 in the sand-cast condition and is devoid of the brittleness which is found in a white iron. The hardness is due to the excessive hardness of the carbides and the peculiar manner in which they are intermingled and interlaced with the hard, tough solid solution. The long spine-like needles occur in a characteristic palmate structure which is depicted in Fig. 6.

Forged low-carbon alloys have been tested at elevated temperatures and average results are as follows:

TEMPERATURE, DEG. CENT.	TENSILE STRENGTH, LB. PER SQ. IN.
100	116 000
400	109 000
500	95 000
600	52 000
700	18 000
800	8 500
900	5 000

CONCLUSIONS

Enough has been said to indicate the possibility of wide application for chromium-iron alloys in many branches of the chemical and related industries. While many combinations are possible with other metals, so far as we know at present any such alloy, to be commercially practicable, must contain chromium in a relatively considerable amount.

It is believed that great possibilities exist for the utilization of alloys of the general type discussed in this paper, for low-temperature carbonization of fuel, recuperator design, and, in general, all forms of apparatus in which a high thermal conductivity and a high tensile strength can advantageously be combined with the oxidation resistance of a refractory. These three requirements, when successfully met, certainly do much to improve the thermal efficiency of chemical processes and thus conserve fuel.

The author gratefully acknowledges the assistance of Mr. F. M. Becket to whose prevision much of the progress in this line has been due; also that of Mr. S. M. Norwood, who has conducted important laboratory work in the development of the high-chromium alloys.

CHARACTERISTICS OF MATERIAL FOR VALVES OPERATING AT HIGH TEMPERATURES

J. B. Johnson[1] and S. A. Christiansen[2]

The selection of the proper material for exhaust valves for aircraft engines involves an analysis which takes into consideration characteristics which are not usually considered essential for other machine parts. One of the most important of these characteristics is the resistance to corrosion at high temperatures.

The valves referred to in this paper are of the poppet type with either mushroom or tulip-shaped heads. They are hot-forged from rolled bar stock which has been carefully selected, generally on a basis of a macro-etch in order to eliminate any bars which may have a piped or spongy core. The reduction from the bar to the forging is approximately 80 per cent. The forgings are annealed, machined, rough-ground, straightened, hardened, finish-ground, and polished.

The valve operates under a tension-impact load, the temperature varying from practically atmospheric at the tip or tappet end to as high as 1600° F. in the head. The temperature gradient is a function of the guide in which the valve is reciprocating, and for any particular design is affected by the material in the guide, the amount it shrouds the stem, and the clearance between the valve stem and the inner surface of the guide. The temperature of the head is affected by the width of the valve seat and the area of the cross-section of the stem. The cooling effect of the valve guide is shown in Fig. 1. The specimen was cut from the stem of a valve forged from a 14-per-cent-chromium steel and represents a section adjoining the head and extending into the guide. The valve had been hardened all over and run for 94 hours in a Liberty-12 engine. The gray band on the specimen on the left is a deposit of copper formed by immersing for 30 seconds in a 10-per-cent aqueous neutral cuprammonium chloride solution. It marks the portion of the stem exposed to the flame when the valve is open and shows the sharp cooling effect of the guide. The hardness determinations indicate that softening did not extend beyond this band. The specimen on the right was subjected to a prolonged etching of 15 hours in the same solution, which brings out sharply the difference between the soft upper portion and the hard lower portion of the stem.

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[1] Chief, Material Section, Engineering Division, Air Service, McCook Field, Dayton, Ohio.

[2] Power Plant Section, Engineering Division, Air Service, McCook Field, Dayton, Ohio.

The head and upper section of the stem are subjected not only to high temperatures, but also to the corroding action of a gasoline and air mixture and the corroding and eroding actions of the hot exhaust gases passing through the valve port at a velocity of from 150 to 200 ft. per second. These gases invariably contain some free oxygen, together with carbon monoxide, carbon dioxide, nitrogen, and other gases in small amounts. The scaling of a valve not only gradually reduces the cross-sectional area, but the loose scale may also become attached to the seat of the valve; this prevents the valve from seating and causes overheating.

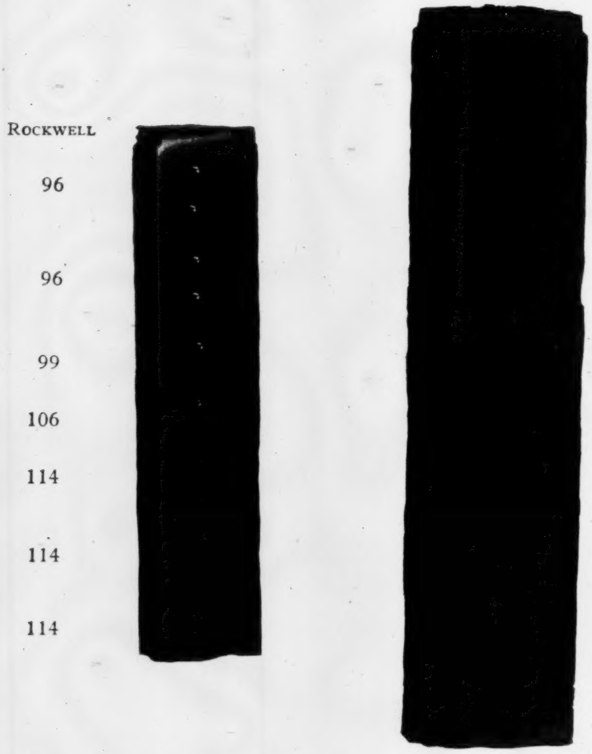
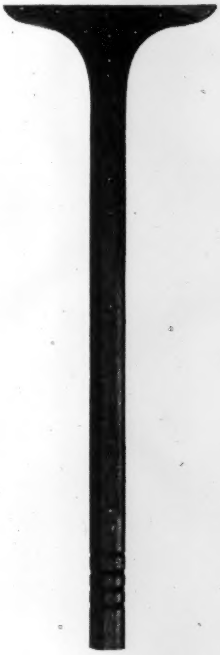


FIG. 1.—Section of Valve Stem, 14-per-cent-Chromium Steel (× 1.5), Illustrating Cooling Effect of Valve Guide.

The valve is actuated by a mechanism that applies a wiping action which is accompanied by a slight blow on the tip of the stem and a side thrust on the guide. These effects are reduced to a minimum by good design, but they are always present and require a hard, wear-resisting surface on the valve stem and tip.

These severe operating conditions have led to the development of special alloys and heat treatments which will meet the requirements to a certain degree, but the ideal valve material has not yet been made. The most successful of the alloys are manufactured with iron as the base metal, with the addition of one or more of the alloying elements—nickel, chromium, tungsten, silicon, molybdenum, cobalt and vanadium—in various proportions.

512 BRINELL 196



BEFORE SERVICE		AFTER 50-HR. SERVICE	
ROCKWELL	SCLEROSCOPE	ROCKWELL	SCLEROSCOPE
111	..	93	23
97	28	98	28
97	27	97	30
95	..	98	28
112	..	113	..
118	..	118	..
119	68	120	65

FIG. 2.—Effect of Operating Temperatures on the Hardness of 14-per-cent-Chromium Valve Steel. See Table I for Chemical Composition and Heat Treatments.

HARDNESS

The hardness requirements are met by special heat treatments. A typical example of differential hardening and the effect of subsequent operating temperatures is shown in Fig. 2. The valve was forged from 14-per-cent chromium steel (C) and heat-treated in accordance with the procedure shown in Table I. The head and tip are originally harder than the stem. The operating temperature was sufficient to draw the head back from a Brinell hardness of 512 to 196.

TABLE I.—CHEMICAL COMPOSITION AND HEAT TREATMENT OF VALVES.

Symbol	Heat Treatment	Chemical Composition, per cent					
		Carbon	Manganese	Silicon	Chromium	Nickel	Other Elements
T....	Heat 2100° F.—Quench in oil Reheat 1325° F.—Cool in air Harden tip[1]	0.50 to 0.70	0.30 (max.)	...	3.0 to 4.0	....	Tungsten 15.0 to 18.0
C....	Heat[2] 1500° F. Cool 50° per hr. to 1100° F., all over Heads—Heat 1700° F. Quench in oil Reheat 900° F. Cool in air Tips—Heat 1750° F Cool in air	0.25 to 0.40	0.50 (max.)	....	11.5 to 14.0	....	....
SC..	Heat[2] 1925° F.—Quench in oil Reheat 1450° F.—Cool in air Harden tip—Heat 1925° F.—Quench in oil Reheat 400° F.—Cool in air	0.45 to 0.60	0.50 (max.)	2.75 to 3.75	7.0 to 9.0	....	...
CN...	None	0.30 to 0.40	0.50 (max.)	3.0 to 4.0	15.0 to 20.0	24.0 to 26.0	....
CC..	Heat 1650° F.—Cool 50° per hr. to 1300° F. Cool in air	1.0 to 1.50	0.50 (max.)	0.40 to 0.60	11.0 to 13.0	....	Molybdenum 0.60 to 0.90 Cobalt 3.0 to 3.50
M.....	None	....	3.50 (max.)	0.50 (max.)	....	60.0 (min.)	Copper 23.0 (min.) Iron 3.50 (max.)

[1] Reheat tip with oxy-acetylene flame, and cool in air with head and stem immersed in water.

[2] These valves manufactured by the Steel Products Co., and record of heat treatments furnished by them.

TABLE II.—PHYSICAL PROPERTIES OF VALVE STEMS AT HIGH TEMPERATURES.

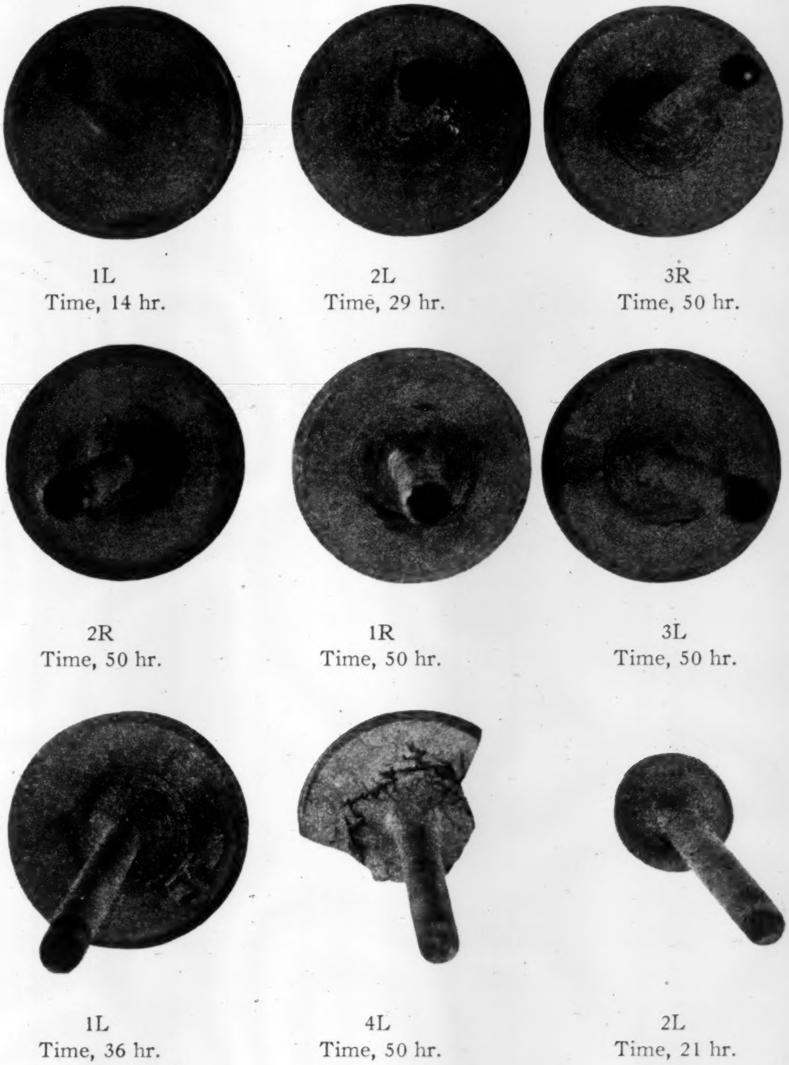
For chemical compositions and heat treatments, see Table I.

Material	Symbol	Temperature of Test, deg. Fahr.	Tensile Strength, lb. per sq. in.	Elongation in 1 in., per cent	Reduction of Area, per cent	Hardness		
						Head	Stem	
						Brinell	Scleroscope	Rockwell[a]
Tungsten Steel	T	70	202 000	4	12	402	42	113
		1200	56 000	35	79	...	..	...
		1400	18 600	60	94	...	..	...
		1500	16 700	69	86	...	..	...
		1600	17 300	60	85	...	..	...
Chromium Steel	C	70	101 000	21	62	500	25	90
		1200	22 000	60	90	...	..	...
		1400	10 500	72	98	...	..	...
		1500	8 500	90	99	...	..	...
		1600	14 700	...	.	...	..	...
Silicon-Chromium Steel	SC	70	208 000	14	39	260	55	116
		1200	42 600	55	91	...	..	...
		1400	14 200	54	90	...	..	...
		1500	8 450	75	92	...	..	...
		1600	4 000	116	77	...	..	...
Chromium-Nickel Steel	CN	70	122 500	29	44	214	25	88
		1200	......	..	..	...	..	...
		1300	52 200	23	..	...	..	...
		1500	23 000	40	..	...	..	...
		1600	24 000	..	.	...	..	...
Cobalt-Chromium Steel	CC	70	124 000	14	27	375	30	100
		1200	52 700	36	60	...	..	..
		1400	18 170	60	80	...	..	...
		1500	12 850	45	85	...	..	...
		1600	18 200	60	70	...	..	...
Monel Metal	M	70	102 000	30	60	112	12	81
		1200	34 100	32	34	...	..	...
		1400	......	..	..	...	..	...
		1500	15 900	20	24	...	..	...
		1600	......	..	..	...	..	...

[a] Ball $\frac{1}{16}$-in. diameter "B" Scale.

PROPERTIES AT HIGH TEMPERATURES

The strength of valve material at atmospheric temperature is important only in so far as it is a function of the hardness. For highly stressed valves, however, the strength at high temperatures is important, and it is necessary to select a material which does not



1L Time, 14 hr.

2L Time, 29 hr.

3R Time, 50 hr.

2R Time, 50 hr.

1R Time, 50 hr.

3L Time, 50 hr.

1L Time, 36 hr.

4L Time, 50 hr.

2L Time, 21 hr.

Fig. 3.—Progressive Failure of Liberty Exhaust Valve, 18-per-cent-Tungsten Steel, Wide Open Throttle, 1700 R.P.M. Compression Ratio 5.4:1.

show a decrease in the original strength sufficient to cause distortion or failure. The progressive failure of an 18-per-cent tungsten steel valve operating under severe conditions is shown in Fig. 3. This failure is typical of a large valve (diameter 2.75 in.) of the mushroom type. The failure shown in Fig. 4 is typical of a small mushroom valve or of the tulip type valve.

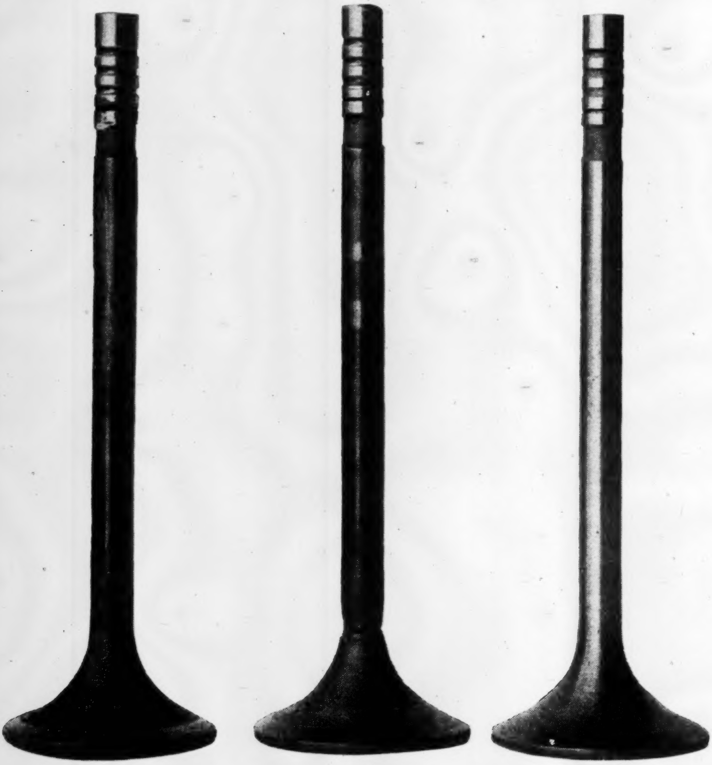


FIG. 4.—Failure of Chromium Tulip Valves after Running in Engine 3 hr. at Full Throttle. Carbon, 0.42 per cent; Chromium, 12.8 per cent.

The results of several tests at temperatures from 1200 to 1600° F. are shown in Table II. These tests were made on specimens cut from valve stems which had been finished preparatory to installing them in an engine. On account of the small diameter of the stems it was necessary to cut proportional test specimens with a gage diameter of 0.25 in. and a gage length of 1 in. A specially wound furnace was used to produce the high temperatures required. The specimens were soaked for 20 minutes at the temperatures of the test after the conditions had come to equilibrium. The temperatures were measured by two thermo-couples—one a platinum-platinum plus 10 per cent rhodium, and the other a chromel-alumel—both of which were in contact with the specimens. The tests were performed in an Olsen testing machine. The pulling speed was 0.03 in. per minute until the specimen had reached its maximum load and the load had fallen off 100 lb. The speed was then increased, keeping the beam balanced until the specimen broke. A study of these results indicates that a combination of 15 per cent chromium and 25 per cent nickel added to iron gave the smallest decline. The addition of 18 per cent tungsten is the equivalent of 3 per cent cobalt with 12 per cent chromium, but the residual strength is less than the nickel-chromium combination. The addition of chromium or silicon and chromium has the least effect.

TABLE III.—CHEMICAL COMPOSITION AND OXIDATION TESTS OF STEEL DISKS.

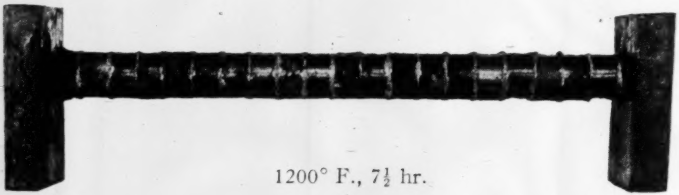
Material furnished by Rich Tool Co. in form of a roll of disks separated by sheets of mica.
Chemical analysis by Rich Tool Co. Original heat treatment unknown.
Disks subjected to oxidizing atmosphere of electric furnace.

Steel No.	Chemical Composition, per cent								Temperature at which Scaling begins, deg. Fah.	Appearance at	
	C	Mn	Si	Cr	Ni	Mo	W	Co		1400° F.	1600° F.
5	0.47	0.59	3.42	9.18	....	....	....	....	1600	Blue	ELS
16	0.38	0.83	3.02	18.58	25.84	....	....	....	1600	Blue	SS
2	0.49	....	2.81	7.80	.....	0.78	....	....	1600	Blue	VLS
11	1.12	.	1.03	12.17	....	0.81	....	2.47	1600	Blue	SS
17	1.52	0.34	0.39	13.16	0.63	1.05	....	1.25	1600	Blue	SS
19	0.36	0.77	1.40	14.07	19.11	....	....	....	1600	Brown	VLS
14	1.18	1.47	1.19	18.3	55.2	....	....	....	1600	Brown	VLS
9	0.46	....	0.96	14.14	0.77	....	....	....	1600	Brown	SS
18	0.47	0.53	3.21	7.89	.....	0.90	3.15	....	1500	Blue	VLS
15	0.31	0.31	3.42	3.33	.....	....	....	....	1300	SS	SS
1	3.58	0.59	2.04	.....	.....	....	....	....	1200	SS	SS
7	0.54	0.80	1.12	8.01	19.32	....	....	....	1400	MS	MS
6	0.50	....	0.92	7.51	.....	....	....	....	1100	MS	MS
10	0.67	....	0.23	3.81	....	....	14.09	....	1100	HS	HS
12	0.18	0.67	0.19	0.22	3.53	....	....	....	1100	MS	MS
3	0.42	0.62	0.17	0.56	1.23	....	....	....	1100	HS	HS
4	0.58	0.71	....	1.10	1.29	....	....	....	1100	HS	HS
13	0.10	0.34	0.07	0.15	4.76	....	...	....	1100	HS	HS
8	0.62	0.32	0.31	0.72	.....	....	2.18	....	1100	HS	EHS

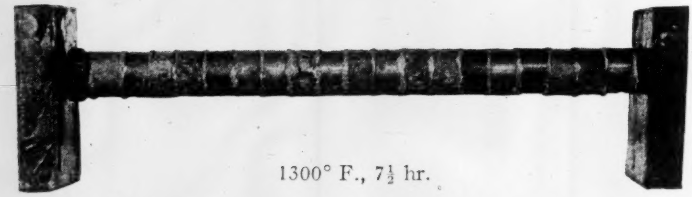
ELS = extra light scale.
VLS = very light scale.
HS = heavy scale.
SS = slight scale.
MS = moderate scale.
EHS = extra heavy scale.

RESISTANCE TO CORROSION

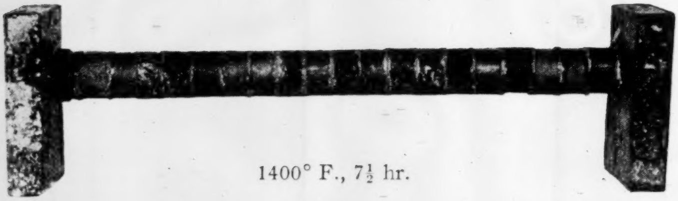
The corrosion of the various materials has been studied from the laboratory standpoint by submitting several steels to the action of the oxidizing atmosphere of an electric furnace. The materials were furnished by Mr. Robert Jardine of the Rich Tool Co. in the form of



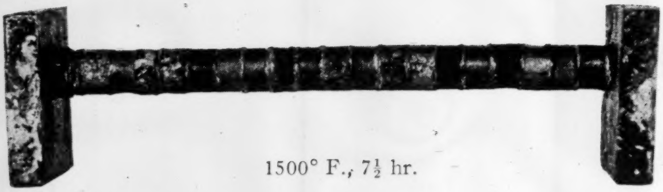
1200° F., 7½ hr.



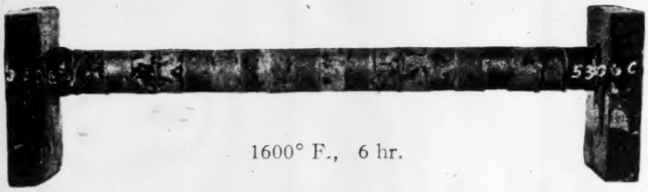
1300° F., 7½ hr.



1400° F., 7½ hr.



1500° F., 7½ hr.



1600° F., 6 hr.

FIG. 5.—Scaling of Various Steels at High Temperature. See Table III for Chemical Compositions.

a roll of disks separated by sheets of mica. The original heat treatment of the disks is unknown. The chemical analysis is shown in Table III. The disks were all bright polished before being placed in the furnace. They were held in the furnace at successive heats of 1200, 1300, 1400, 1500, and 1600° F. for a period of 7½ hours, except the 1600° F. heat, which was discontinued at the end of a 6-hour period due to trouble with the automatic control on the furnace. At the expiration of each period they were removed and photographed.

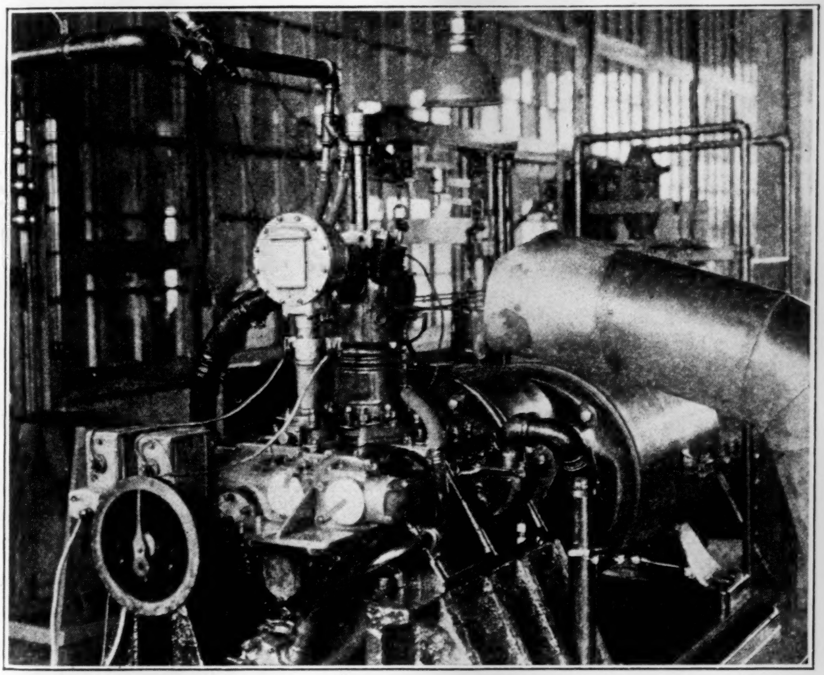


FIG. 6.—Single-Cylinder Test Engine.

These photographs are reproduced in Fig. 5. The classification of each is based upon the amount of corrosion or scaling which could be detected by visual examination. The limitation of the test to one set of specimens and the qualitative nature of the method gives a general classification rather than a specific rating for the material. There is little to choose between steels of any group classified according to the temperature at which scaling begins. However, a similar test made on a quantitative basis would not be an entirely suitable measure of the serviceability of the material for exhaust valves, since

Table IV.—Single-Cylinder Engine Data.

Bore	5.5 in.
Stroke	6.5 in.
Displacement	154.4 cu. in.
Compression ratio	5.4:1
Brake horse-power	43.0
Specific fuel consumption	0.520 to 0.54 lb. per h.p. hr.
Brake M.E.P	118 to 124 lb. per sq. in.
R. P. M	1800
Piston speed	32.5 ft. per sec. or 1950 ft. per min.

Valves

Port diameter	1.75 in.
Maximum lift	0.39 in.
Mean lift inlet	0.26 in.
Mean lift exhaust	0.27 in.

Gas Velocities with 2 Valves Each

Exhaust with maximum lift	180 ft. per sec.
Exhaust with mean lift	199 ft. per sec.

Springs	Outer	Inner
Wire size	0.148 in.	0.120 in.
Outside diameter	1.5625 in.	1.125 in.
Number of effective coils	8	10
Load to compression to 2 in	33.5 lb.	22.5 lb.
Length of spring, valve closed	2 in.	2 in.

Timing (Designed)

Intake opens	10 deg. A.T.C.
Intake closes	50 deg. A.B.C.
Exhaust opens	40 deg. B.B.C.
Exhaust closes	10 deg. A.T.C.
Intake tappets	0.015 in.
Exhaust tappets	0.020 in.

Conditions of Test

Duration of run		50 hr.
Throttle opening		Fully opened
Engine speed		1800 r.p.m.
Compression ratio		5.4:1
Oil pressure		37 lb. per sq. in.
Water temperature	in	160° F.
	out	170° F.
Oil temperature	in	120° F.
	out	155° F.
Spark advance for best power		26–30 deg. normal, 28 deg. B.T.C.
Number of spark plugs used		2, placed 180 deg. apart
Operating temperatures		1420–1520° F.

The temperatures were read by means of a Leeds and Northrup optical pyrometer sighted through the exhaust port on the neck of the valve.

the type of corrosion is also important. For instance, No. 16 shows resistance to scale formation, but tends to pit, and these pits are more troublesome on a valve seat than a uniform scale.

TESTS UNDER OPERATING CONDITIONS

Single-cylinder Engine Tests.—The characteristics of the materials were determined under actual operating conditions by running the valves for 50 hours in a single-cylinder test engine. Fig. 6 shows the test engine and test engine set-up, and Fig. 7 shows a cross-section of the cylinder. The engine data and the condition of test are given in Table IV. The construction of the valve mechanism allowed considerable slippage between the tappet and valve tip and gave a side pressure on the stem a little more severe than would be expected from a normal valve gear. Fig. 8 shows valves which have been through a 50-hour test. The corrosion on the valve head can be plainly seen. The scale formation is the maximum on the tungsten (T) valve and the minimum on the chromium nickel (CN). The slight scaling on the chromium, silicon-chromium, and cobalt-chromium valves would not interfere to an appreciable extent with the operation of the valve.

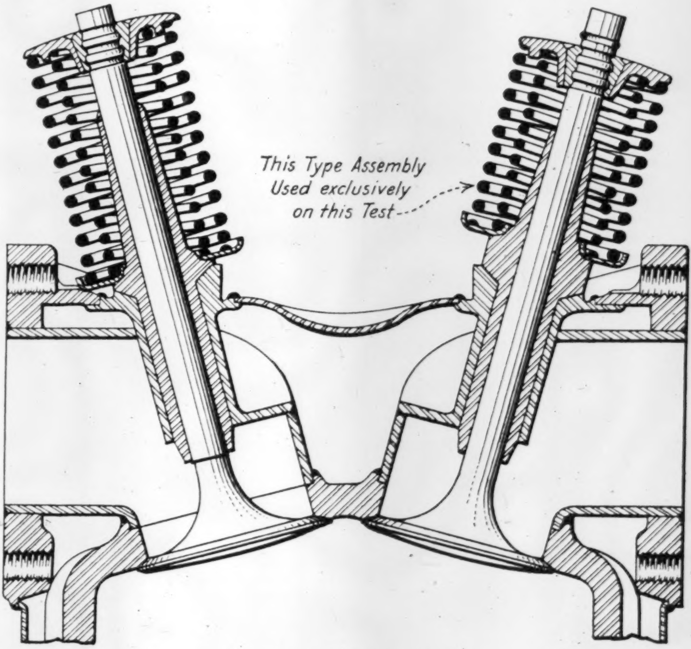


FIG. 7.—Cross-Section of Single-Cylinder Test Engine.

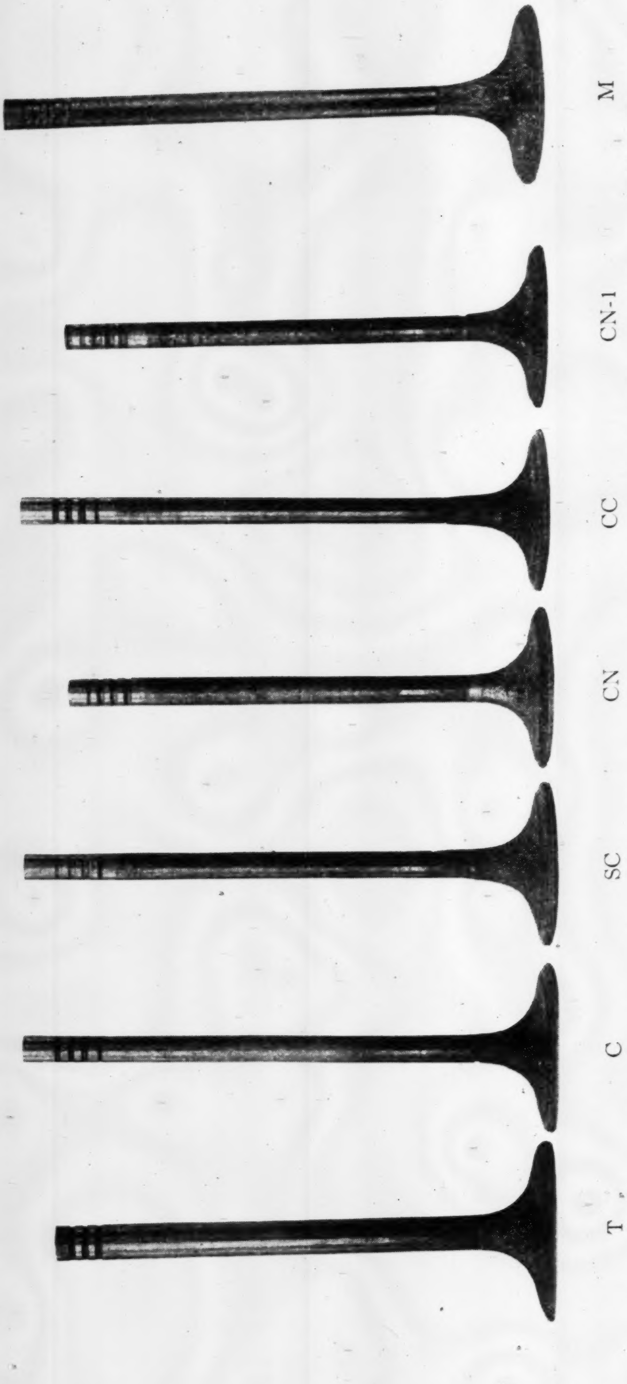


FIG. 8.—Stem and Head Condition of Valves after 50-hr. Engine Test. See Table I for Chemical Composition and Heat Treatment.

Another characteristic which this photograph shows is the conditions of the valve stem. The tungsten steel retains its original hardness and shows a highly polished stem with only a slight pick-up at the head end. The cobalt-chromium valve shows even better stem conditions. The pick-up is more pronounced on silicon-chromium and chromium steels and is comparatively heavy on the remaining three valves. In fact, the stems of these three valves are so soft that the galling is serious enough to eliminate them from consideration as valve materials for air-craft engines.

TABLE V.—HARDNESS, CONDITION AND APPEARANCE OF VALVES AFTER COMPLETING 50-HOUR TEST IN SINGLE-CYLINDER ENGINE.

Guide Material, Cast Iron.

The chemical analyses of steels are given in Table I, except CN-1, which is

Carbon	0.40 per cent
Silicon	1.25 "
Chromium	6.50 "
Nickel	20.0 "

The heat treatments are the same as in Table I, except SC and CC:

SC ..... Anneal at 1900° F.; cool in furnace. Reheat tips to 925° F.; quench in oil. Reheat to 400° F.; cool in air.

CC ..... Heated to 1830° F; quenched in oil. Reheat to 1050° F.

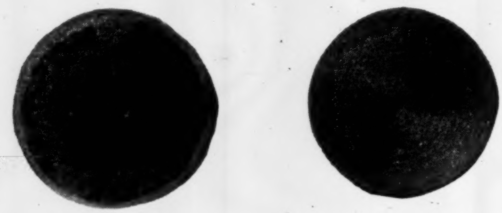
Valve Material	Hardness Determinations			Condition and Appearance						
	Head,[a] Brinell	Stem, Rockwell	Tip, Scleroscope	Stem		Tappet	Valve Seat	Stem Wear, in.		
				Head End	Middle and Tappet End					
T	370 - 400	95 - 110	65 - 70	Good ...	Very slight pick-up	Excellent	HS	0	0	0
C	172 - 200	90 - 95	70 - 75	Poor	Slight scoring	Bad	SS	0.0030	0.0005	0.0007
SC	250 - 280	100 - 110	65 - 75	Fair	Very slight pick-up	Excellent	SS	0.0007	0.0003	0.0005
CN	200 - 230	80 - 90	45 - 55	Very bad	Slight scoring.....	Very bad	MS	0.0025	......	0.0050
CC	270 - 300	110 - 115	70 - 80	Excellent	Very slight pick-up	Excellent	MS	0	0	0
M	112	75 - 85	25 - 30	Fair	Slight scoring.....	Very bad	MS	0.0016	......	0.0003
CN-1....	207	85 - 95	45 - 55	Very bad	Bad scoring	Unusable	MS	0.0019	No data	0.0009

HS = heavy scale.
MS = moderate scale.
SS = slight scale.

[a] For original hardness, see Table II, except SC = 296, CC = 525.

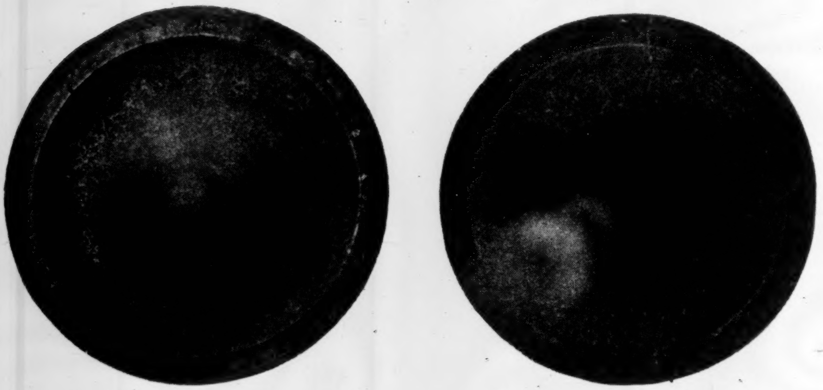
Hardness determinations were made on the valves after running and are given in Table V. The Brinell hardness was taken on the top of the valve at the center of the head. The stem readings were taken at five positions on the stem below the section affected by the flame. The stem hardness, therefore, does not show the softening effect of the flame, although this is very important and causes considerable galling of the stem and wear on the guide. The amount of galling on that portion of the stem, as well as a general description of condition and appearance, are also given in Table V. The condition of the tips after running is shown in Fig. 9, which shows a tip unaffected by wear and one badly worn. A few heat treatments were tried on the chromium-nickel (CN) steels, but they had practically no effect on the hardness. Seat conditions are shown in Fig. 10. Chromium-nickel (CN-1) steel pitted and oxidized so badly that it caused the valve to leak considerably during the latter part of the test.

18-Cylinder Engine Tests.—The tests in the single-cylinder engine eliminated the chromium-nickel alloys and monel metal from further consideration. The tungsten, chromium, cobalt-chromium and silicon-chromium steels were given further tests in an 18-cylinder engine operating under full throttle conditions at 1800 r.p.m. and developing maximum brake horse-power. The valves were of the same type as those used in the single cylinder engine. The tests of the tungsten-steel valves checked closely the tests in the single-cylinder engine, and although there were no failures, the scale formation was so


CN
Very Bad

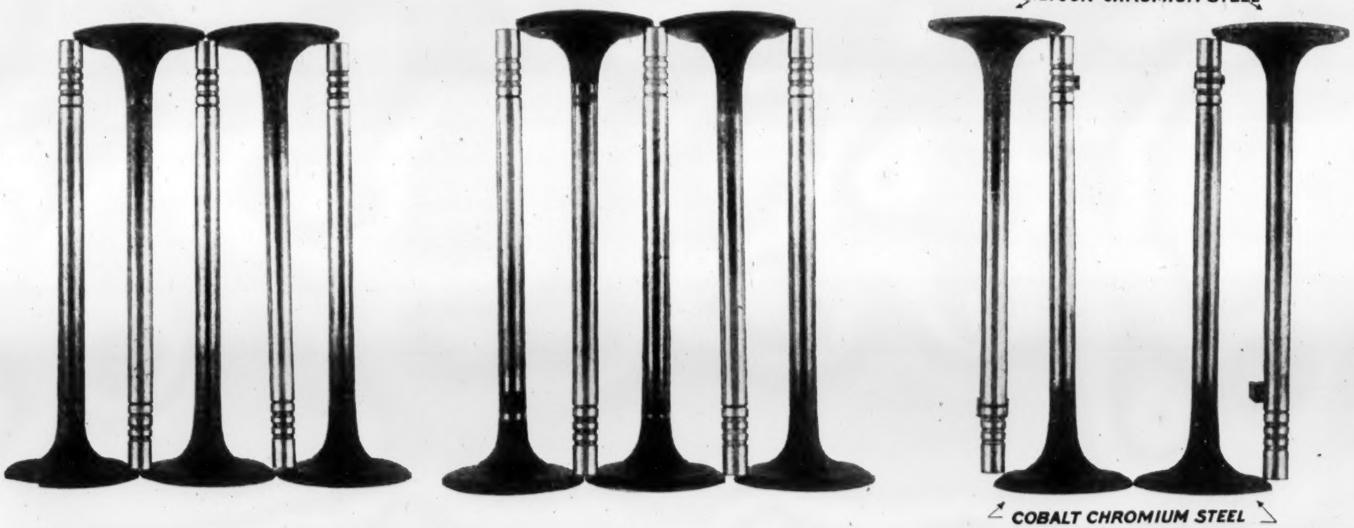
CC
Excellent

FIG. 9.—Tip Condition of Valves after 50-hr. Engine Test. See Table I for Chemical Composition and Heat Treatment.


CN-1
Very Bad

SC
Excellent

FIG. 10.—Seat Condition of Valves after 50-hr. Engine Test. See Tables I and V for Chemical Composition and Heat Treatment.

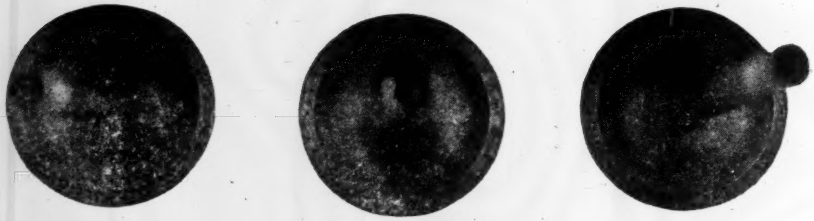

SILICON CHROMIUM STEEL
COBALT CHROMIUM STEEL

(*a*) Cobalt-Chromium Steel; Stems Run in Cast-Iron Guides.

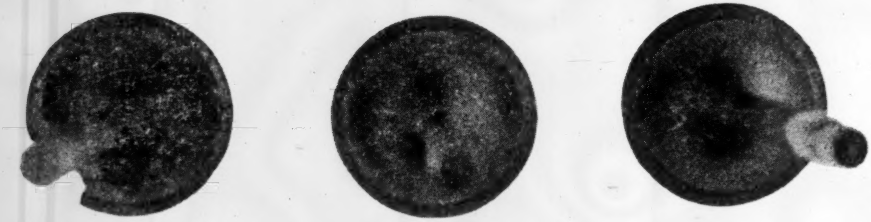
(*b*) Silicon-Chromium Steel; Stems Run in Cast-Iron Guides.

(*c*) Cobalt-Chromium and Silicon-Chromium Steels; Stems Run in Aluminum-Bronze Guides.

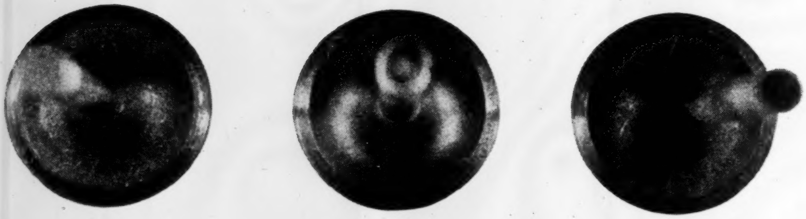
FIG. 11.—Stem Condition of Exhaust Valves after 50-hr., 18-Cylinder Engine Test.



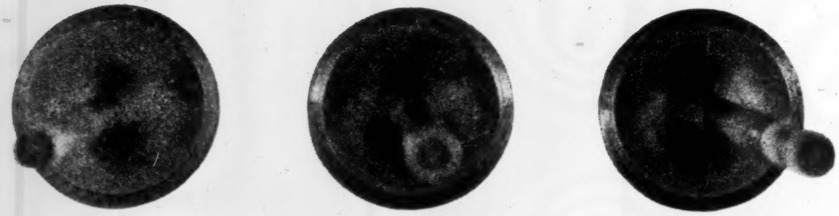
Silicon-Chromium Steel.



Cobalt-Chromium Steel.
(*a*) Three Poorest Valves of Each Type.



Silicon-Chromium Steel.



Cobalt-Chromium Steel.
(*b*) Three Best Valves of Each Type.

FIG. 12.—Seat Condition of Exhaust Valves after 50-hr., 18-Cylinder Engine Test.

heavy that the life of the valves was much reduced. The substitution of chromium steel reduced the scaling considerably, but failures occurred in the neck of the valve. This was remedied by increasing the thickness of the head $\frac{1}{32}$ in. and increasing the cross-section of the neck by making the stem taper into the head with a larger radius. The stem condition, however, of the chromium steel valves was not satisfactory due to the galling with aluminum-bronze guides and excessive wear with cast-iron guides. The tests were repeated, using silicon-chromium and cobalt-chromium valves. Neither of these materials scaled badly, but the silicon-chromium steel exhibited the same weakness as the chromium steel.

These preliminary experiments resulted in a 50-hour test being made on the silicon-chromium and cobalt-chromium steels in the same engine, using the valves with the increased dimensions. Figs. 11 and 12 show the condition of these valves after this test. Fig. 11 (*a*) and (*b*) show the condition of the cobalt-chromium and silicon-chromium valves run in cast-iron guides. In a multi-cylinder engine, conditions are not exactly the same in all of the cylinders, and these unequal conditions led to the failure of some of the cobalt-chromium valves by burning. This type of failure was not experienced with the silicon-chromium valves. The stems of the cobalt-chromium valves, however, were in much better condition than those of the silicon-chromium valves. This is illustrated in Fig. 11 (*c*). The two valves on the left represent the best silicon-chromium and best cobalt-chromium and the two on the right the worst silicon-chromium and worst cobalt-chromium, when operating in aluminum-bronze guides. The seat conditions are shown in Fig. 12, (*a*) representing the three poorest valves of each type and (*b*) the three best valves. The hardness of both the cobalt-chromium and silicon-chromium valves was affected by the operating temperatures. The initial hardness of the cobalt-chromium averaged 525 and the silicon-chromium 300; the final hardness was 294 and 259, respectively.

SUMMARY

The operating temperature of the exhaust valve depends largely upon cylinder and valve design. If the valves are running black no trouble is experienced, but if a temperature of 1500° F. is approached, the limitations of the various materials must be considered.

The quarternary alloys of iron, chromium, nickel, and silicon, in which the range of chromium is from 6 to 15 per cent and the nickel 20 to 25 per cent, cannot be used in air-craft engine valves, since they cannot be hardened sufficiently to prevent excessive galling of the stems and wear on the tips. The ternary alloys of iron, chromium, and tungsten are not satisfactory on account of heavy scaling. Chromium steel is not satisfactory, as it loses its hardness at high temperatures, which causes a galling of that portion of the valve stems subjected to the action of the exhaust flame. Cobalt-chromium steel gives the best stem conditions, but has a tendency to scale and burn in the head, although not to the same degree as tungsten steels. It is satisfactory except under unusual operating conditions. The ternary alloys of iron, silicon, and chromium satisfy the requirements of a valve steel in so far as the head and seat conditions are concerned, but they have the same drawback as the chromium steel in regard to softening of the stem in the section which is exposed to the action of the flame when the valve is open, but to a less degree.

The authors wish to acknowledge the assistance of Mr. Samuel Daniels and Mr. Stephen W. Thompson in connection with the tests.

SOME ELECTRICAL PROPERTIES OF HIGH-RESISTANCE ALLOYS

By M. A. Hunter[1] and A. Jones[2]

Introduction

The recent advances in the art of electrical heating have stimulated research in the field of high-resistance alloys. In the last ten years many new combinations of the metals have been suggested as resistor materials and some of them have rendered very satisfactory service. The new alloys are for the most part binary and ternary mixtures of the more common metals. A review of the literature discloses a considerable amount of information on the specific resistances of these alloys and also on their temperature coefficients between room temperature and 100° C. Little information will be found, however, on the same electrical properties at the high temperatures at which the material is required to operate.

The present paper gives, in an attempt to supply this need, a summary of these important physical constants for some of the well-known high-resistance alloys.

The attempt to use the high-resistance alloys as elements in base-metal thermocouples for the measurement of temperature was only a natural step in the development. In the second division of the paper some old and some new information has therefore been included on the electromotive forces which may be expected from various combinations of these materials.

Theoretical Considerations

It has already been stated that high-resistance alloys are produced by alloying metals with one another in binary or ternary combinations. It does not follow, however, that all such combinations give materials of high specific resistance.

When two or more metals are melted together they may behave on freezing in two characteristically different ways. When in the molten state the constituents of the alloy are of course minutely dispersed in one another. On freezing they may remain minutely dispersed so that even in a microscopic section the constituents cannot be differentiated. These combinations are known as "solid solutions." The second class of alloys comprises those which on freezing permit the two or more constituents to freeze separately from one another. They no longer remain in solution in the solid state. The microscope can distinguish the separate constituents. These alloys form what is known as "eutectic mixtures" with one another. The metals may, however, in certain concentrations form intermetallic compounds with one another and the compound thus formed may dissolve and subsequently freeze either as a solid solution or as a eutectic mixture with the pure metal which is present. Since these intermetallic compounds are in general hard and brittle materials no great concentrations can be carried in any alloy which has subsequently to be reduced to wire.

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[1] Russell Sage Laboratory, Rensselaer Polytechnic Institute; also Research Division, Driver Harris Co.

[2] Russell Sage Laboratory, Rensselaer Polytechnic Institute.

The electrical properties of these two classes of alloys are very different from one another. In a solid solution the electrical resistance of the resulting alloy bears no relation to the resistances of the components. It is in all cases very materially higher than either. The temperature coefficient of electrical resistance is also changed. Whereas the individual constituents have temperature coefficients approximately equal to 0.004 per degree Centigrade, the temperature coefficient of the solid solutions drops very rapidly with increasing concentrations of the added component. In some cases it drops to zero and may even in special cases become negative. In eutectic mixtures, however, no such radical variations are produced. The electrical resistances of these alloys approximate in the main to the mean of the electrical resistances of the components while the temperature coefficient, if it drops at all, does so to only a slight degree.

It is therefore evident that high-resistance alloys belong in the class of solid solutions. It is further to be noted that such combinations will yield alloys with temperature coefficients which are considerably lower than the pure metals from which they are made.

MATERIALS USED FOR HIGH-RESISTANCE ALLOYS

The metallic combinations which are commercially available for high-resistance materials are made in general from nickel, iron or copper, melted in binary or ternary combinations with manganese or chromium. All of these metals are comparatively cheap, are available in sufficient quantity for commercial production and resist oxidation satisfactorily over the range of temperature which limits their use. For the purpose of classification we may divide the various alloys into three groups:

Group A.—Materials of high resistance available for units running at temperatures below 500° C.;

Group B.—Materials of high resistance for units running at temperatures above 500° C.; and

Group C.—Materials having special properties other than high resistance used in units at room temperature.

TABLE I.—VARIATION IN RESISTANCE OF A NUMBER OF MATERIALS WITH TEMPERATURE

Expressed as the ratio of resistance at the various temperatures to resistance at 20° C.
For complete chemical compositions, see Table II.

Temperature, deg. Cent.	Electrolytic Nickel	Grade A Nickel	Grade C Nickel	Grade D Nickel	Monel	Advance	Alloy No. 141	Alloy No. 193
20........	1.00	1.00	1.00	1.00	1.000	1.000	1.00	1.000
100........	1.45	1.43	1.36	1.29	1.160	0.9992	1.40	1.093
200........	2.07	2.06	1.90	1.68	1.215	0.9995	1.93	1.198
300........	2.86	2.83	2.58	2.10	1.255	1.002	2.54	1.292
400........	3.69	3.52	3.02	2.31	1.295	1.006	3.20	1.365
500........	4.00	3.87	3.26	2.46	1.340	1.020	3.96	1.425
600........	4.31	4.15	3.49	2.62	1.385	1.039	4.78	1.472
700........	4.62	4.44	3.73	2.78	1.435	.....	4.94	1.504
800........	4.93	4.73	3.96	2.94	1.485	.....	5.06	1.538
900........	5.24	5.04	4.22	3.13	1.550	.....	5.20	1.585
1000........	5.64	5.38	4.50	3.32	1.630	.....	5.33	.....

SPECIFIC RESISTANCE AT 20° C., OHMS PER MIL-FOOT

58.6	64	84	117	268	290	124	530

TABLE II.—CHEMICAL COMPOSITIONS OF THE MATERIALS REPORTED IN TABLE I.

The analysis given for alloy No. 193 is an approximate analysis only. The other values given are the actual analyses on samples used to obtain the results detailed in Table I.

Material	Nickel	Copper	Iron	Carbon	Manganese	Silicon	Chromium
Electrolytic Nickel.......	99.80	0.05	0.15	....	....	....	....
Grade A Nickel..........	98.85	0.24	0.65	0.08	0.08	0.03	...
Grade C Nickel..........	96.15	0.40	0.89	0.22	2.10	0.18	...
Grade D Nickel..........	94.10	0.16	0.74	0.08	4.75	0.13	...
Monel..................	68.10	27.66	2.40	0.16	1.50	0.11	...
Advance................	44.00	54.00	0.45	....	1.16	....	...
Alloy No. 141............	69.33	0.16	28.86	0.22	1.30	0.13	...
Alloy No. 193............	30.00	.....	67.00	0.22	1.00	....	2

GROUP *A*.—ALLOYS FOR USE BELOW 500° C.

The alloys in this group have nickel as their major component. Nickel alone has usually been considered to be unsatisfactory by reason of its low specific resistance at room temperature. Nickel has, however, two valuable properties which render it useful as a resistor material. It resists oxidation at elevated temperatures better than any of the commoner metals. It has further a high temperature coefficient of electrical resistance, the effect of which on the electrical resistance at high temperature is indicated in subsequent tables.

Nickel can be obtained commercially in several grades. The purest obtainable is electrolytic nickel and following in order of lesser purity are Grade A, Grade C and Grade D. Intentional additions of manganese in the two latter affect to a considerable degree the electrical properties of the material.

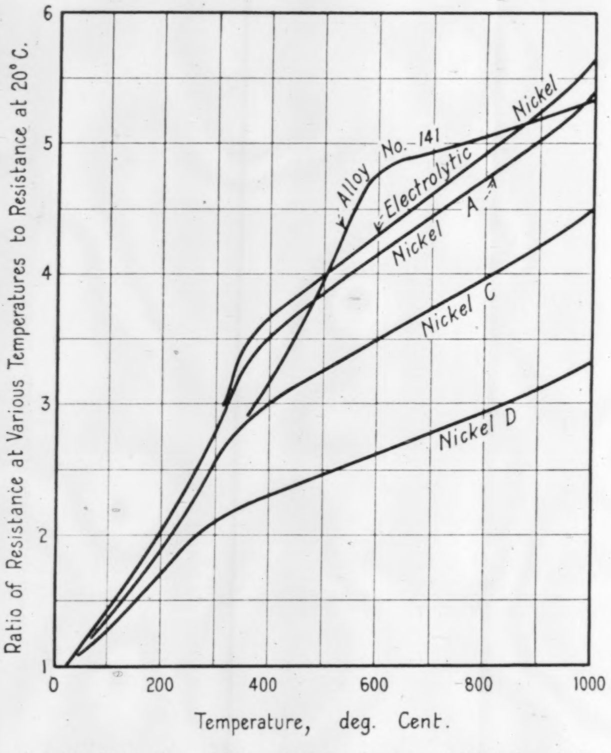

FIG. 1.—Showing the Variation of Electrical Resistance of Nickel and Certain Nickel Alloys at Various Temperatures.

Values plotted are given in Table I, chemical compositions in Table II.

The specific resistance of nickel can be increased by the addition of metals which form solid solutions with it. The commonest additions are copper and iron. Among the nickel-copper alloys are monel and Advance, the former having a preponderating amount of nickel, the latter of copper. Among the nickel-iron alloys used, the most important are alloy No. 141 and alloy No. 193, the former having an excess of nickel, the latter an excess of iron.

The variations in resistance of samples of these materials at various temperatures and their specific resistances at 20° C. are given in Table I. The chemical compositions of the wires used in these observations are given in Table II.

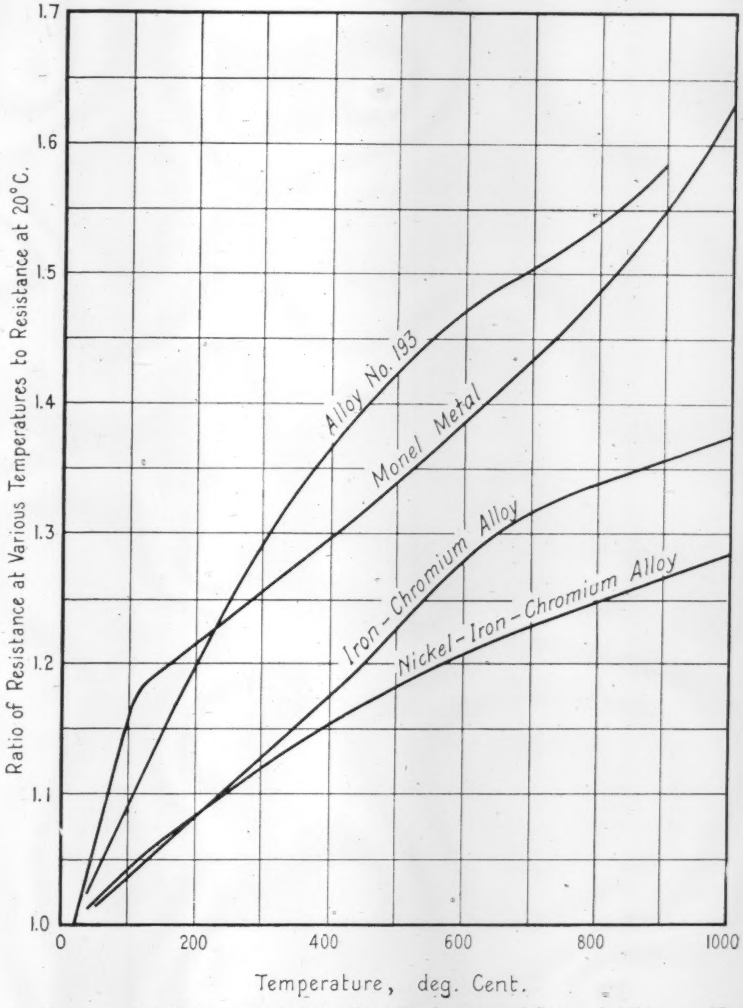

FIG. 2.—Showing the Variation of Electrical Resistance of Several Alloys at Various Temperatures.

Alloy No. 193 }
Monel } Values plotted are given in Table I, chemical compositions in Table II.

Nickel-Iron-Chromium Alloy.—Values plotted are for Alloy No. 4, Table IV; for chemical composition see Table V.

Iron-Chromium Alloy.—Values plotted are for Alloy No. 1, Table VI; for chemical composition see text.

The values given in Table I, with the exception of those for Advance, are plotted as a function of the temperature in Figs. 1 and 2. These curves are characteristic of the various grades of nickel and monel metal. Slight variations in composition will of course change the actual values for the resistance at any temperature, but the trend of the curve remains the same. The change in slope of each curve is due to the fact that at the corresponding temperature the metal is changing from the magnetic to the non-magnetic condition. The transformation points as obtained from the curves are as follows:

Grade A Nickel	350° C.
Grade C Nickel	320° C.
Grade D Nickel	275° C.
Monel Metal	93° C.

The values given for Advance in Table I indicate a peculiar property in this metal. The temperature coefficient is negative over the lower ranges of temperatures, increases slowly between 200 and 400° C. and rapidly thereafter. Not all samples of Advance, however, give negative temperature coefficients in the lower range. The presence of impurities in the metal may yield a material with a low positive coefficient over this lower range. But the rapid rise in temperature coefficient in the higher ranges of temperature is general in all cases.

Alloy No. 141 is peculiarly susceptible to heat treatment. A sample of the material when slowly cooled after annealing gives a much lower specific resistance and a higher temperature coefficient than one which has not been so treated. The values reported in Table I are for the second heat on wire which was slowly cooled after being taken up to 1000° C. After this treatment the wire appears to be stable for further cycles of heat. Slight variations in the impurities also have a very considerable effect. Therefore, while this alloy is excellent as a high-resistance material, it is difficult to reproduce in commercial production.

Alloy No. 193, as will be seen from Table I, is an exceedingly good resistor up to 500° C. and has received in consequence wide application. The resistance-temperature curve for this material is plotted in Fig. 2.

GROUP *B*.—MATERIALS AVAILABLE FOR TEMPERATURES IN EXCESS OF 500° C.

The second group includes all those alloys which are essentially combinations of nickel, iron and chromium in various proportions Most of these alloys have been worked under a patent granted to Marsh in February, 1906, which has now expired. These alloys are remarkable in that they possess very high specific resistances and resist oxidation at high temperatures to a very marked degree. The specific resistances and temperature coefficients at room temperature have been known for some time but information on these points at the temperatures of operation is meager or entirely lacking. It has generally been assumed that the temperature coefficient of the alloy was uniform throughout the whole range of temperatures used, an assumption which, as will be seen from the following tables, is very far from the truth.

For convenience in classification the alloys are divided into three sub-groups:

1. Nickel-chromium alloys;
2. Nickel-iron-chromium alloys;
3. Iron-chromium alloys.

TABLE III.—VARIATION IN RESISTANCE OF ALLOYS OF NICKEL AND CHROMIUM WITH TEMPERATURE.

Expressed as the ratio of resistance at the various temperatures to resistance at 20° C.

Temperature, deg. Cent.	Nichrome III								Nichrome IV			
	No. 5	No. 6	No. 1	No. 4	No. 11[a]	No. 10	No. 13	Mean	A	B	C	D[1]
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
300	1.055	1.034	1.047	1.037	1.057	1.040	1.039	1.043	1.034	1.027	1.026	1.025
400	1.066	1.047	1.063	1.051	1.068	1.051	1.053	1.056	1.046	1.036	1.032	1.036
500	1.073	1.060	1.071	1.063	1.075	1.060	1.063	1.066	1.060	1.045	1.041	1.042
600	1.071	1.058	1.074	1.061	1.074	1.058	1.062	1.065	1.055	1.036	1.034	1.032
700	1.072	1.060	1.077	1.062	1.077	1.063	1.065	1.068	1.056	1.032	1.030	1.028
800	1.074	1.066	1.088	1.068	1.086	1.072	1.073	1.075	1.063	1.033	1.031	1.028
900	1.082	1.076	1.100	1.094	1.096	1.083	1.083	1.088	1.074	1.038	1.032	1.030
1000	1.097	1.090	1.118	1.104	1.112	1.098	1.099	1.103	1.090	1.049	1.046	1.040
SPECIFIC RESISTANCE AT 20° C., OHMS PER MIL-FOOT												
	604	604	564	567	599	595	553	.....	575	620	629	633
PERCENTAGE OF CHROMIUM												
	14.10	14.45	15.40	15.60	15.70	15.80	16.20	.....	17.47	18.18	18.70	18.95

[a] Plotted in Fig. 3 as typical of Nichrome III.
[1] Plotted in Fig. 3 as typical of Nichrome IV.

Nickel-Chromium Alloys.—The simplest and best combination is the binary alloy of nickel and chromium. Alloys containing as high as 25 and 30 per cent of chromium have been made. It is commercially practicable to make alloys containing 15 and 20 per cent of chromium. In general it may be said that the resistance to oxidation bears a direct relation to the amount of chromium in the wire. This is certainly true for chromium contents up to 20 per cent and probably holds for higher percentages. For temperatures below 1000° C., alloys of the Nichrome III class containing 15 per cent of chromium have given good service. For the range between 1000° C. and 1100° C. alloys of the Nichrome IV class, containing 18 to 20 per cent of chromium, are advisable. While these alloys may be used for short periods at temperatures above 1100° C. their life under these conditions is exceedingly short.

The variations in resistance of some of these nickel-chromium wires and their specific resistances at room temperatures are given in Table III. Typical resistance-temperature curves are plotted in Fig. 3. These results indicate an interesting peculiarity which seems to be inherent in all nickel-chromium wires. In the case of the Nichrome III alloys (15 per cent chromium) the resistance-temperature curve rises at a uniform rate up to 500° C. From 500 to 700° C., the curve runs practically parallel to the temperature axis, indicating a zero temperature coefficient over this range. Above 700° C. the resistance rises sharply again. In the Nichrome IV series (18 to 20 per cent chromium) the same general trend is followed except that between 500 and 700° C. the wire has a marked negative temperature coefficient. This can be readily seen in Fig. 2 on which the values for the two representative nickel-chromium wires are plotted.

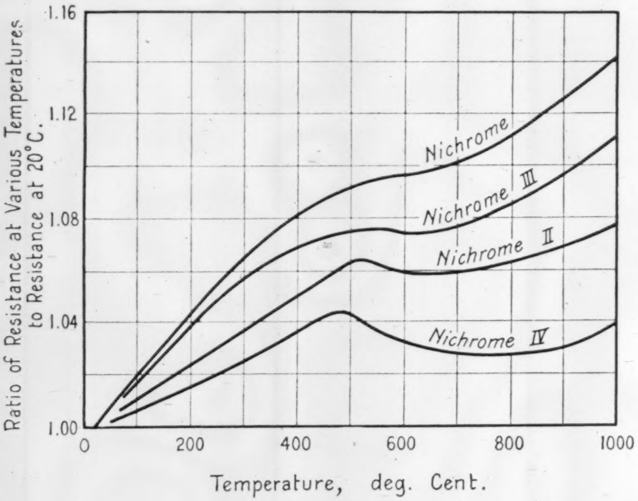

Fig. 3.—Showing the Variation of Electrical Resistance of Nickel-Chromium and Nickel-Iron-Chromium Alloys at Various Temperatures.

Nichrome III.—Values plotted are for Alloy No. 11, Table III; chromium, 15.70 per cent.
Nichrome IV.—Values plotted are for Alloy D, Table III; chromium, 18.95 per cent.
Nichrome—Values plotted are for Alloy No. 7, Table IV; for chemical composition see Table V.
Nichrome II.—Values plotted are for Alloy No. 1, Table IV; for chemical composition see Table V.

The reason for this change in slope of the resistance temperature curve at 500° C. is not at present understood. It is not a magnetic transformation point since the materials themselves are non-magnetic at room temperatures. In the absence of a better explanation we may conclude that it is due to a change in the molecular configuration of the elements in the wire.

TABLE IV.—VARIATION IN RESISTANCE OF NICKEL-IRON-CHROMIUM ALLOYS WITH TEMPERATURE

Expressed as the ratio of resistance at the various temperatures to resistance at 20° C.
For complete chemical compositions, see Table V.

Temperature, deg. Cent.	Nichrome						Nichrome II		Other Alloys	
	No. 2	No. 3	No. 8	No. 12	No. 9	No. 7[a]	No. 1[b]	No. 2	No. 3	No. 4[c]
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
300	1.091	1.086	1.092	1.071	1.073	1.065	1.037	1.038	1.048	1.120
400	1.113	1.104	1.110	1.089	1.090	1.081	1.050	1.050	1.061	1.154
500	1.126	1.120	1.125	1.102	1.105	1.092	1.063	1.062	1.075	1.182
600	1.132	1.125	1.129	1.106	1.108	1.096	1.059	1.058	1.076	1.208
700	1.142	1.133	1.134	1.111	1.115	1.102	1.059	1.057	1.079	1.227
800	1.152	1.141	1.141	1.118	1.124	1.113	1.063	1.059	1.084	1.247
900	1.165	1.154	1.154	1.130	1.136	1.127	1.069	1.065	1.090	1.266
1000	1.182	1.172	1.171	1.148	1.150	1.142	1.078	1.072	1.098	1.284
SPECIFIC RESISTANCE AT 20° C., OHMS PER MIL-FOOT										
	633	640	689	665	654	663	668	683	686	622
PERCENTAGE OF CHROMIUM										
	10.75	10.90	11.05	11.45	11.70	12.05	19.5	17.95	31.35	21.10

[a] Plotted in Fig. 3 as typical of Nichrome.
[b] Plotted in Fig. 3 as typical of Nichrome II.
[c] Plotted in Fig. 2.

TABLE V.—CHEMICAL COMPOSITIONS OF THE NICKEL-IRON-CHROMIUM ALLOYS REPORTED IN TABLE IV.

All Values are per cent

Alloy		Nickel	Iron	Chromium	Manganese
Nichrome	No. 2	59.29	28.70	10.75	1.54
	No. 3	59.02	27.86	10.90	1.54
	No. 8	59.57	26.97	11.05	1.69
	No. 12	61.75	24.97	11.45	1.19
	No. 9	62.00	24.35	11.70	1.46
	No. 7	61.20	24.88	12.05	1.44
Nichrome II	No. 1	.....	.....	19.5	.....
	No. 2	69.35	10.53	17.95	1.58
Other Alloys	No. 3	53.58	13.77	31.35	0.00
	No. 4	27.62	48.45	21.10	0.85

Nickel-Iron-Chromium Alloys.—Of all the alloys in this class, the alloy known as Nichrome has received the most extended application. This alloy contains approximately 60 per cent of nickel, 26 per cent of iron and 12 per cent of chromium. It has a higher specific resistance than a straight nickel-chromium alloy and a somewhat higher temperature coefficient. It resists oxidation satisfactorily at temperatures up to 900° C. For temperatures in excess of this, it should be replaced by a nickel-chromium alloy substantially free from iron.

Nichrome II is a nickel-iron-chromium alloy of intermediate composition. It has less iron and more chromium than Nichrome.

Attempts have been made from time to time to diminish the nickel content of this class of materials. But under these conditions, to maintain the high resistance to oxidation it becomes necessary to increase proportionately the chromium content.

The electrical properties of this group of alloys are given in Table IV. The chemical compositions of the wires used in these observations are given in Table V. Typical resistance-temperature curves are plotted in Fig. 3.

TABLE VI.—VARIATION IN RESISTANCE OF IRON-CHROMIUM ALLOYS WITH TEMPERATURES.

Expressed as the ratio of resistance at the various temperatures to resistance at 20° C.

TEMPERATURE, DEG. CENT	No. 1[a]	No. 2
20	1.000	1.000
300	1.129	1.132
400	1.175	1.174
500	1.225	1.235
600	1.278	1.283
700	1.316	1.322
800	1.338	1.341
900	1.357	1.355
1000	1.375	1.365

[a] Plotted in Fig. 2 as typical of Iron-Chromium Alloy. The specific resistance at 20° C. of alloy No. 1 was 583 ohms per mil-foot.

Iron-Chromium Alloys.—The iron-chromium alloys have up to the present received but little attention. Some of these materials, however, have been introduced on the market so that some mention should be made of them. The alloys contain approximately 75 per cent of iron and 22 per cent of chromium, the high content of chromium being necessary to overcome the tendency of the iron to oxidize. The silicon content sometimes runs as high as 2 per cent. From the manufacturer's standpoint the material is hard to draw, especially if the silicon content is relatively high. The alloys withstand oxidation fairly well but they are inferior to the nickel-chromium alloys. Another radical objection observed was that the wire under continued heating tended to increase permanently in length.

Observations on the electrical properties of two of these wires are given in Table VI The chemical compositions of the two wires are as follows:

	No. 1	No. 2
Iron, per cent	75.10	74.62
Chromium, per cent	22.06	22.23
Nickel, per cent	0.87	1.17
Silicon, per cent	1.67	1.24
Carbon, per cent	0.18	0.65

The values obtained for wire No. 1 are plotted in Fig. 2.

GROUP C.—MATERIALS WITH SPECIAL PROPERTIES

The third class of alloys to be considered includes those materials that have some special properties which render them useful under restricted conditions. The fact that pure nickel has a remarkably high temperature coefficient of electrical resistance is made use of in the construction of resistance thermometers. Again, the fact that Advance and manganin have remarkably low temperature coefficients is applied in the construction of precision resistances.

Electrical Properties of Pure Nickel.—Two samples of nickel wire were obtained directly from electrolytic sheet. A section cut from the sheet was rolled to wire. The material was therefore not contaminated by impurities which usually enter during melting. From these wires the following results were obtained:

ELECTROLYTIC NICKEL	SPECIFIC RESISTANCE, MICROHM CM.	TEMPERATURE COEFFICIENT, PER DEG. CENT.
No. 1	7.55	0.00559
No. 2	7.60	0.00553

Temperature coefficient is expressed in ohms per degree Centigrade per ohm at 20° C., over the range from 20 to 50° C. The coefficient for No. 1 is equivalent to a value of 0.00629 per ohm at 0° C.

It is, however, not feasible to produce such material on a commercial scale. The metal must be melted in large quantities, cast into ingots, forged and drawn into wire. The effect of manganese additions used for deoxidation at the end of the melting operation was found to be as follows:

MANGANESE ADDED, PER CENT	TEMPERATURE COEFFICIENT
0.25	0.00460
0.63	0.00452
1.00	0.00357

The time of melting is a material factor. A succession of small melts were made in an electric furnace. For the first melt the furnace required 45 minutes to reach the melting point of nickel. The second, third, and fourth melts required progressively shorter times; the last melt was cast 12 minutes after the introduction of the cold charge. The following results were obtained from the separate melts:

Melt No.	Time of Melting, minutes	Specific Resistance, microhm cm.	Temperature Coefficient
1	45	9.75	0.00448
2	20	8.80	0.00462
3	..	8.67	0.00484
4	..	8.64	0.00484
5	12	9.12	0.00490

An analysis of the material from melt No. 5 showed the following constituents: Nickel 99.22 per cent, manganese 0.59 per cent, iron 0.14 per cent, copper 0.03 per cent, and carbon 0.00 per cent. This material should be somewhat purer than those from the four preceding melts, since it was exposed for a shorter time to furnace gases and crucible lining.

These experiments indicate the conditions to be observed in order to secure nickel wire with the highest possible temperature coefficient of electrical resistance. The nickel should be the purest available. The additions of manganese (or magnesium) must be as small as is compatible with subsequent forgeability. The time taken to melt should be a minimum in order that the molten material should be exposed for as short a time as possible to the effect of the furnace gases. If these conditions are met, a high-grade nickel wire can be produced.

Materials with Zero Temperature Coefficients.—Advance and manganin have been mentioned as alloys which have special applications as materials for precision resistances by reason of the fact that they have temperature coefficients which approximate to zero over restricted ranges of temperature.

Advance contains as major constituents approximately 55 per cent of copper and 45 per cent of nickel. An alloy containing these materials only has a pronounced negative temperature coefficient at 20° C. The material as commercially produced, however, contains small amounts of impurities such as iron, manganese, carbon and silicon which are present either in the raw materials used or are taken up during the melting. The general effect of these impurities is to increase the temperature coefficient of the material. The extent of this change, as produced by the above impurities, is now under consideration and will be reported on at a later time.

Manganin is a ternary alloy having as its major constituents 84 per cent of copper, 12 per cent of manganese and 4 per cent of nickel. The effect of small variations in these constituents is at present under investigation. It is interesting to note that the condition of the surface of the wire modifies its temperature coefficient to a pronounced degree. Wire made from material of the composition given above has a negative coefficient over the range from 20 to 50° C. If, however, the wire has been superficially oxidized either by exposure to moist air or heat, the manganese is selectively oxidized leaving a metallic skin of copper on the wire. If this superficial skin is more than a few thousandths of an inch in thickness, the wire takes on an appreciable positive temperature coefficient. As in the case of the Advance wire, the presence of small amounts of impurities in

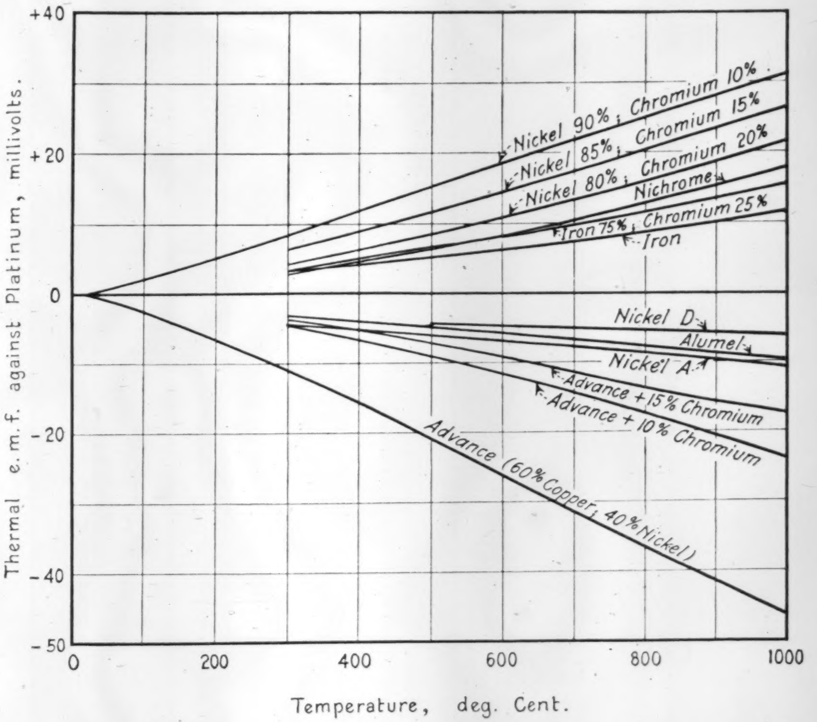

FIG. 4.—Showing Thermal Electromotive Forces of Various Metals and Alloys Against Standard Platinum.

manganin appears to modify this temperature coefficient. These phenomena are, however, still being studied and will not be further discussed here.

THERMAL ELECTROMOTIVE FORCES OF ALLOYS

The fact that the various alloys described in the preceding section give widely varying electromotive forces renders certain combinations exceedingly useful as base-metal thermocouples for the measurement of temperature.

TABLE VII.—THERMAL ELECTROMOTIVE FORCES OF VARIOUS METALS AND ALLOYS AGAINST STANDARD PLATINUM.

COLD JUNCTION, 20° C.

Temperature, deg. Cent.	Alloys Positive to Platinum					Alloys Negative to Platinum					
	Nickel-Chromium Alloys			Iron	Iron Chromium Alloy 25% Cr	Nickel Alloys			Copper-Nickel Alloys		
	10% Cr	15% Cr	20% Cr			A	D	Alumel	Advance (60% Cu, 40% Ni)	Advance + 15% Cr	Advance + 10% Cr
300.....	8.35	6.20	4.20	3.30	3.25	4.38	....	3.10	11.00	3.60	4.64
400.....	11.78	8.88	6.18	4.28	4.86	5.20	....	3.96	15.82	5.22	6.74
500.....	15.27	11.72	8.47	5.12	6.52	5.96	4.38	4.88	21.08	7.10	9.10
600.....	18.61	14.56	10.76	6.06	8.11	6.72	4.78	5.89	26.24	9.24	11.62
700.....	21.99	17.39	13.34	7.34	9.87	7.58	5.14	6.86	31.46	11.53	14.38
800.....	25.17	20.42	16.07	8.82	11.58	8.48	5.46	7.76	36.48	13.78	17.32
900.....	28.30	23.50	18.80	10.20	13.50	9.56	5.80	8.70	41.35	15.70	20.50
1000.....	31.23	26.53	21.68	11.58	15.47	10.62	6.14	9.57	46.32	17.12	23.76

TABLE VIII.—THERMAL ELECTROMOTIVE FORCES OF VARIOUS COMBINATIONS.

COLD JUNCTION 20° C.

Temperature, deg. Cent.	Ni 90%, Cr 10%, with Alumel	Iron with Advance	Ni 90%, Cr 10%, with Advance	Ni 85%, Cr 15%, with Advance	Ni 80%, Cr 20%, with Advance	Nichrome with Advance	Ni 90%, Cr 10%, with Advance +15% Cr
300............	11.45	14.30	19.35	17.20	15.20	13.90	11.95
400............	15.74	20.10	27.60	24.70	22.00	20.40	17.00
500............	20.15	26.20	36.25	32.80	29.55	27.40	22.37
600............	24.50	32.30	44.90	40.80	37.05	34.55	27.85
700............	28.85	38.80	53.45	48.85	44.80	41.90	33.52
800............	32.93	45.30	61.65	56.90	52.55	49.25	38.95
900............	37.00	51.55	69.65	64.80	60.15	57.60	44.00
1000............	40.80	57.90	77.60	72.85	68.00	64.20	48.35

The combinations of iron and Advance (Constantan) and of Chromel (10 per cent of chromium in nickel) with Alumel (1 to 2 per cent of aluminum in nickel) are already well known and widely used. The former gives an e.m.f. of approximately 58 millivolts at 1000° C. and the latter approximately 41 millivolts. The thermal e.m.f.'s of these materials and of other alloys of nickel or iron and chromium are given in Table VII, in which alloys that are positive to a sample of pure platinum chosen as a standard and alloys that are negative to the same sample of platinum are listed separately. The values given in this table have been plotted in Fig. 4. The alloys of Advance (copper 55 per cent, nickel 45 per cent) with chromium, whose thermal e.m.f.'s against platinum are given in the last three columns of Table VII, were made with the view of obtaining a material that would be more resistant to oxidation than the old Advance wire. Among the nickel-chromium alloys, the 90 per cent nickel - 10 per cent chromium combination gives the highest electromotive force, but the 80-20 material is good and of course resists oxidation to a greater degree.

An examination of Table VII reveals some suggestive combinations for securing electromotive forces considerably in excess of that given by the first two well-known couples. Some of these combinations are given in Table VIII.

Acknowledgment.—The authors desire, in conclusion, to express their appreciation of the assistance given during the progress of the work by the technical staff of the Driver-Harris Co.

CHARACTERISTICS OF SOME MATERIALS FOR BASE-METAL THERMOCOUPLES

BY F. E. BASH[1]

In the last ten years the use of thermocouples in this country for measuring temperatures in industrial work has become so widespread as to be almost universal. Temperature control of processes and heat treatment of various materials have been worked out with the aid of different types of thermocouple with the greatest degree of satisfaction; as a result, guesswork has been eliminated and much more uniform products produced.

Every instrument manufacturer and many users of temperature apparatus would like to be able to obtain a thermocouple suited for all needs. This is an ideal toward which we may aim and may hope to approach. The ideal thermocouople is one that will give a high electromotive force and stand continuous high temperatures under oxidizing or reducing conditions without deterioration mechanically or loss of calibration. Its temperature - e.m.f. relation should be such that the calibration curve should be a straight line or a continuous smooth curve without any breaks or reversals. In addition, it is very important that the elements from which it is made be ductile enough to permit of being drawn into wire.

There are two general types of thermocouple in use to-day, the noble and base metal, which are made, as their names indicate, from noble and base metals. In industrial work, the noble-metal couple is practically always made from pure platinum and an alloy of platinum and 10 per cent of rhodium. Iridium and other metals have been used in different combinations. The base-metal thermocouples have been made mostly from iron and constantan, copper and constantan, and alloys of nickel and chromium with nickel-aluminum and copper-nickel. The electromotive force of noble-metal couples is generally small as compared with the base metal, but they can withstand so much higher temperatures that in work requiring control above the working range of base-metal couples, they are used. The chief objections to them, in addition to the low electromotive force, are ease of contamination and high cost. Their advantages are ability to stand high temperatures, freedom from oxidation, and accuracy of calibration. Base-metal thermocouples have, however, a wide application because of their generally high electromotive force, low cost, and robustness in service. Their accuracy is not so great but is sufficient for most industrial purposes.

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Materials for the elements of thermocouples can be divided into two classes, pure metals and alloys. In general, combinations of pure metals which are suitable for industrial thermocouples give a low electromotive force. When the pure metals are used with certain alloys, however, some very satisfactory combinations have been worked out. There are also a number of combinations of alloys which are suitable for thermocouples.

In choosing the elements of a thermocouple the following are important considerations:

1. Reproducibility of both elements as regards calibration.
2. Both elements should have as nearly as possible the same melting point.
3. Both elements should have the same resistance to corrosion and oxidation.
4. In general, both elements should be as nearly equal in physical and mechanical properties as possible.

When using a pure metal for one element, it will be found in some cases that the calibration will vary from one lot of metal to another. This is due to small differences in the amount of impurities present and it is often found very difficult to control them. The same conditions are true of alloys. For this reason, when manufacturing either pure metals or alloys for thermocouples, it is practically necessary to have other uses for the material that is not within calibration limits; otherwise, the cost would be prohibitive.

We have found what properties the ideal couple should have and what are the most desirable type of combinations. No one has yet developed a thermocouple that combines all the desirable features. There still remains the possibility of developing an alloy or alloys that will approach more nearly the ideal than any yet disclosed, as there are so many possible combinations of metals that have not been tried.

In order to determine suitable thermocouple elements, it is necessary to have some method of standardizing and checking the different materials and putting them upon a standard basis for comparison. In the past, all published curves for high-temperature thermo-electric properties have been of different combinations of metals and alloys in which no particular metal was used as a basis of comparison. Physicists have used lead as a basis of comparison for low-temperature work and a number of metals have been standardized against it.[1]

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[1] Smithsonian Physical Tables.

As a result, the thermal electromotive force for any combination of two metals at these low temperatures can be readily calculated. The characteristics of metals and alloys at the high temperatures are not always the same as at the boiling point of water, so that it is desirable to have some other reference standard than lead, which melts below a red heat.

There are two metals available which can be obtained in a high state of purity. One is copper, the other is platinum. Tests were made a few years ago by Irving B. Smith on samples of copper wire taken from a wide range of sources and manufacturers. He found in all cases that it ran uniform in thermo-electric properties. It is reasonable that it should, on account of the high degree of purity of all copper wire. It has the advantage of being cheap and not easily contaminated like platinum and is very easily obtainable anywhere. A small copper wire will stand at least one heating to 1800° F., which is sufficient to make a determination on any sample of thermocouple material.

If all material tested for its desirability as an element in a base-metal thermocouple were checked against copper at 1500° F., or a curve plotted between room temperature and 1800° F., it would then be an easy matter to determine its characteristics combined with other materials by making an algebraic subtraction of the electromotive force between each metal and copper for any temperature and plotting the curve.

In order to test a number of metals and alloys for thermocouple purposes, tests were run on constantan, manufactured under the trade name of "Ideal," and later a number of other alloys against copper. The tests were made as follows: A couple was made up between the metal to be tested and copper by welding them together at one end and insulating with porcelain beads. The hot junction of this couple was then bound to the hot junction of a standard Iron-"Ideal" couple which had been carefully checked. The two hot junctions were then surrounded by a mass of copper to make sure they were at the same temperature. They were placed in a vertical cylindrical electrical furnace 10 in. in diameter by 14 in. deep on a block of Sil-o-cel. The two cold ends were attached to a two-point potentiometer recorder and the furnace started. Cold junction compensation was automatically taken care of on the standard couple. On the test couple, it was calculated after the test and the correction made before plotting the curve. The furnace was brought to 1800° F. in about four hours. The recorder gave a record of the temperature in the furnace and the corresponding millivoltage of the piece being tested against copper.

The guaranteed accuracy of the recorder was 0.25 per cent and the accuracy of the standard couple ± 10° F. The results gave the shape of the curves for each metal and their approximate e.m.f.-temperature relation. This test was repeated with a number of alloys, with the results shown in Fig. 1. The alloys tested are listed in Table I with their approximate analysis. The method of testing was rapid as the test ran itself once it was started.

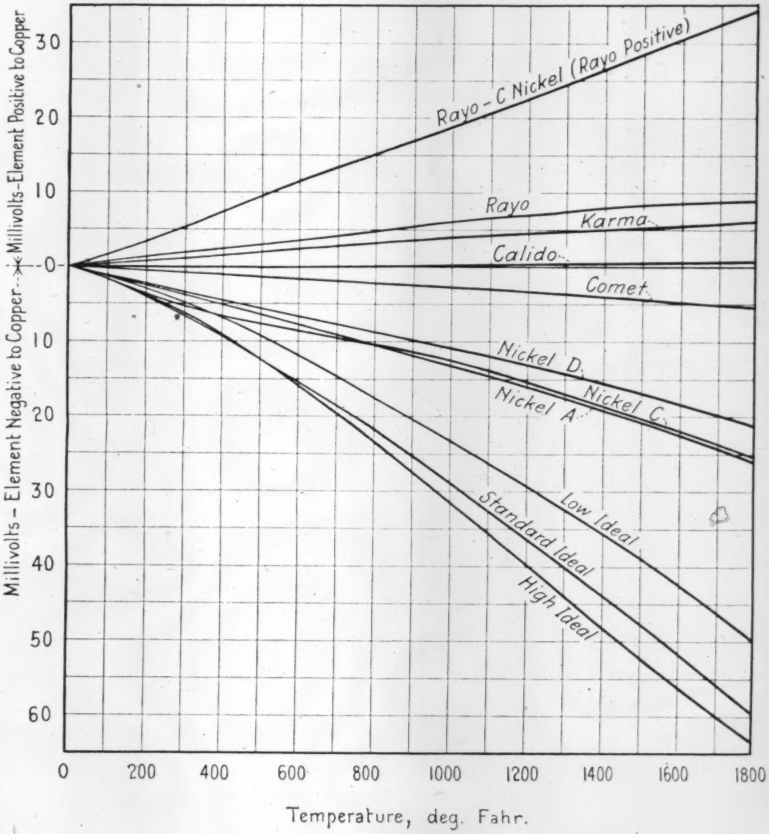

FIG. 1.—MILLIVOLT-TEMPERATURE CURVES FOR VARIOUS METALS AND ALLOYS AGAINST COPPER AS A STANDARD

When a metal is found that has the characteristics desired for a particular purpose, a careful check can be made using a potentiometer and standard noble-metal couple. The characteristics of any combination of two metals can also readily be calculated by running only the one test against copper.

In Fig. 1 are shown the temperature - e. m. f. curves for the eight alloys listed in Table I. It will be noted that the nickel-chromium alloys are all positive[1] to copper, though Calido gives practically no electromotive force with it, the highest e.m.f. being 0.6 millivolt at 1800° F. It is probable that a very slight change in composition would make it coincide with copper and give no e.m.f. when coupled with it. In this respect it is possible that it might replace copper in the "Ideal" (constantan) copper couple that is used quite extensively at low temperatures. This would extend the range to higher temperatures where copper can not be used, due to oxidation.

Comet, which is a high iron alloy, is slightly negative to copper, giving only 5 millivolts at 1800° F. The curve is a smooth one so that it is suitable for thermocouple work and is used with Ideal for that purpose. The pure nickel, nickel-manganese, and nickel-copper alloys are all negative to copper, the one giving the largest electromotive force being Ideal.

TABLE I.

Alloy	Nickel, per cent	Chromium, per cent	Copper, per cent	Manganese, per cent	Iron, per cent
Karma	80.0	20	..	...	..
Rayo	85	15	..	...	..
Calido	62	15	..	...	23
Comet	30	5	..	...	65
Ideal (Constantan)	45	..	55	...	..
Nickel A	99.5+	..	..	...	..
Nickel C	97.5+	..	..	2.0	..
Nickel C	95.0+	..	..	4.5	..

Three curves for Ideal have been plotted in Fig. 1, designated Standard, High and Low Ideal. The several references in the paper to Ideal refer to the Standard. The High and Low Ideal curves represent maximum deviation from the Standard in our practice. There is no material difference in the composition, the variations in electromotive force being due to slight differences in the impurities.

In attempting to pick a combination of metals from the curves in Fig. 1 with a large electromotive force, Rayo and Ideal would naturally be selected as being the farthest apart. They have proved excellent for this purpose. In order to check the calculation of a combination of metals, a test was run on the combination of Rayo and C Nickel and the actual curve checked against the theoretical. The curve for the combination is shown in Fig. 1 and it will be noted that it is the algebraic difference between the e.m.f.'s of Rayo and C Nickel at each temperature against copper, giving those metals that are negative to copper a minus sign and *vice versa*. The calculated and actual curves agree within experimental error.

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[1] When a material is spoken of as being positive to copper, it is understood that it is connected to the positive terminal of the instrument used to measure the electromotive force of the couple. In other words, the current is understood to flow toward copper at the cold junction.

CONCLUSION

In conclusion, the author would express a preference for copper as a standard for which to check the suitability of metals and alloys for thermocouples, because of its high degree of purity and the ease of securing it. The method described has proved very satisfactory and it is recommended that all the new thermocouple materials be checked in this way.

GENERAL DISCUSSION

Mr. Price. MR. W. B. PRICE[1] *(presented in written form)*.—Admiralty nickel, a new corrosion- and heat-resisting white metal alloy developed by the writer and given the abbreviated name "Adnic," contains 70 per cent of copper, 29 per cent of nickel and 1 per cent of tin. It is so called from the fact that the proportions of copper and tin are the same as those in regular Admiralty condenser metal, with twenty-nine per cent of nickel replacing the same percentage of zinc.

The alloy has been very successfully used for the manufacture of diaphragms, and has proved to be the only non-ferrous alloy in wire form that will successfully produce the perfect glass beads required in the manufacture of artificial pearls.

Many alloys used in corroding media or at elevated temperatures are refractory, and can only be had in the cast form, but "Adnic," on account of its remarkable ductility, can be drawn, stamped and spun.

Since this metal is especially adapted for the manufacture of diaphragms and was developed for that purpose, a description of its use in diaphragm-operated valves may be of interest.

Thermostatic devices functioning by fluid pressure consist in the assembly of a number of diaphragms or a corrugated bellows forming a chamber which contains the thermostatic fluid. Expansion or contraction occurs with the variation of temperature in the surrounding medium, increasing or decreasing the pressure of the fluid within the chamber. As long as the joints in the thermostat can be maintained tight the fluid pressure will bear a constant relationship to the external temperature.

Variations in the characteristics of the metal due to temperature and operating strains have been and still are a continual source of trouble to manufacturers of thermostatic devices. It is found that a thermostat which functions perfectly when new will, after a short time, operate prematurely. This is due to annealing of the metal by prolonged exposure to high temperature and, in the case of some alloys, due to the rapidly repeated movements to which the metal is subjected. In an attempt to overcome the latter difficulty, the diaphragm metal is frequently made harder and this in turn leads to breakage.

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[1] Chief Chemist and Metallurgist, Scovill Manufacturing Co., Waterbury, Conn.

Extensive tests have shown the copper-nickel-tin alloy to meet the requirements far better than any other alloy investigated within a period of three years, these including phosphor-bronze, nickel, nickel-silver, cupro-nickel, monel and intermediate compositions. **Mr. Price.**

The usual testing method is as follows: Each thermostat to be tested is carefully micrometered and observation made as to its expansion under various internal pressures. It is then placed on a header and immersed in an oil bath at a temperature of 350° F. By means of a reciprocating valve, thermostats in four groups of 16 each are alternately expanded and contracted—the former being caused by admission of air at a pressure sufficient to completely expand the thermostat and the latter by the quick release of air allowing the diaphragms to contract. The rate of expansion is 70 times per minute for eleven hours per day. At intervals of 100,000 operations, the thermostats are removed and retested for permanent set and expansion under various pressures; this is repeated until such time as a permanent condition is reached (usually between 200,000 and 400,000 operations). After reaching a permanent set, the thermostats are tested to destruction without further observations. This test has been used for controlling the suitability of raw material.

In thermostats containing six diaphragms made from the copper-nickel-tin alloy, assembled into a single unit having an over-all length of approximately 1¾ in., it is found that, after one to two million operations, there is an increase in length of only 0.018 to 0.033 in. and a softening represented by a pressure not exceeding 4 per cent less than the original pressure required to give the same expansion. Observations made after ten million operations show no deviation from these results.

A search of the literature failed to reveal that any work had been done on the ternary diagram of copper, tin and nickel, and consequently an investigation of the alpha field of this diagram was made, over the range of the patent. It is hoped at a later date to present a paper giving the full details of this investigation with accompanying micrographs, physical properties, and detailed tests in different corroding solutions.

Mr. C. M. Johnson[1] (*presented in written form*).—The data submitted in the accompanying Table I supplements that incorporated in the tables prepared by the committee arranging this Symposium. **Mr Johnson.**

There are in progress at the present time an extended series of tests designed to determine the resistance of the Rezistal metals in rod or sheet form to most commercial chemicals, at room temperature

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[1] Director, Research and Metallurgical Departments, Park Works, Crucible Steel Co., Pittsburgh, Pa.

TABLE I.—CORROSION DATA ON VARIOUS ALLOYS AND ALLOY STEELS.

All values are expressed in milligrams loss per square inch.

Corroding Medium	Rezistal Alloy[a]		26.00 to 28.00 Chromium Iron		Monel Metal		Sheet Copper		Stainless Steel		Stainless Iron		Chromel (20 per cent Cr., 80 per cent Ni.)		98-per-cent Nickel	
	Room Temperature	90 to 100° C.	Room Temperature	90 to 100° C.	Room Temperature	90 to 100° C.	Room Temperature	90 to 100° C.	Room Temperature	90 to 100° C	Room Temperature	90 to 100° C.	Room Temperature	90 to 100° C.	Room Temperature	90 to 100° C.
Lactic Acid, 25-per-cent	....	**(No. 7)** 0.00 (Bright)	....	991.60 (Jelly)	....	1.27	1.32 (Bright)	2.39 (Bright)	47.3	....	....	....	2.14	1.86	....	3.2
Formic Acid, 85-per-cent	**(No. 7)** 0.25	**(No. 7)** 21.9	0.48	102.7	1.6	3.5 (Av.)	7.21 Adherent oxide	....	37.8	....	46.0	....	3.45	....	2.8	13.2
Formic Acid, 0.34-per-cent	**(No. 7)** 0.50 (Best)	**(No. 7)** 0.00	....	....	1.24	0.76	2.53	....	....	....	....	....	4.17	....	....	....
Potash Alum, saturated solution	**(No. 7)** 0.00	**(No. 7)** 0.00	0.10	0.000	0.26	0.10	0.67	0.50	16.77	....	3.37	34.0	2.12	2.67	1.25 (Av.)	0.50
Citric Acid, saturated solution	**(No. 7)** 0.10	....	0.24	....	0.19	....	0.22	0.31	3.32	....	4.68	....	0.00	....	0.30	....
Citric Acid, 1 part saturated solution, 1 part water	....	**(No. 7)** 0.00	....	0.00	....	0.47	....	0.31	....	28.17	....	125.2	....	1.27	....	0.90
Sulfuric Acid:																
5-per-cent, 7 hours	....	**(No. 8)** 3.15	....	Dissolves freely	....	1.99	1.48	2.30	Dissolves freely		Dissolves freely		2.43	9.00	....	10.58
10-per-cent, 7 hours	....	8.4	....		....	1.90	0.99	2.87					3.38	9.02	....	11.21
20-per-cent, 7 hours	....	12.4	....		....	1.70	0.50	2.10					3.94	22.64	....	11.40
H_2S bubbling through water at boiling temperature, 6 hours	**(No. 9)** Slight discoloration	**(No. 9)** 0.47 **(No. 2600)** 0.00	....	5.8 Bronze-like after removing black smudge	....	2.76 Dark tarnish	....	16.41 Blue black adherent coating	....	0.09 Dark tarnish	.... Very slight tarnish	0.00	....	0.00 Very slight tarnish	1.70 Dark tarnish in patches	....
1 to 1000 Mercuric Chloride sterilizing solution	**(Nos. 7 and 8)** 0.00	No tarnish	No loss, no tarnish		2.93	....	....	....	....	....	....	....	....	....	....	....

[a] Data are here given on Rezistal Alloys Nos. 4, 7, 8, 9 and 2600. The particular alloy in each test is represented by boldface figures.

TABLE I.—CORROSION DATA ON VARIOUS ALLOYS AND ALLOY STEELS.—*Continued.*

Corroding Medium	Rezistal Alloy[a]		26.00 to 28.00 Chromium Iron		Monel Metal		Sheet Copper		Stainless Steel		Stainless Iron		Chromel (20 per cent Cr., 80 per cent Ni.)		98-per-cent Nickel	
	Room Temperature	90 to 100° C.	Room Temperature	90 to 100° C.	Room Temperature	90 to 100° C.	Room Temperature	90 to 100° C.	Room Temperature	90 to 100° C.	Room Temperature	90 to 100° C.	Room Temperature	90 to 100° C.	Room Temperature	90 to 100° C.
85-per-cent Phosphoric Acid	**(No. 7)** **0.00**	**(No. 7)** **0.10**	2.42	....	....	0.10	0.365	0.19	....	....	....	....	5.58	21.03	....	2.80
Acetic Acid, "glacial"	....	**(No. 9)** **0.44**	0.1	29.8	....	3.00	5.550	....	....	....	....	....	20.56	....	5.38	3.08
Acetic Acid 30-per-cent solution	**(No. 9)** 0.00	**(No. 9)** 0.10	....	....	2.52	1.48	3.19	....	12.17	....	0.05	0.130	3.87	....	3.55	....
Gallic Acid, 25-per-cent solution	....	**(Nos. 7 and 9)** 0.00	....	0.16	....	1.33	....	1.90	....	0.26	....	0.86	....	0.00	....	0.35
Ammonium Chloride, saturated solution	....	**(No. 7)** 0.79	....	6.80	....	....	....	3.12	....	....	....	6.7	....	14.1	....	....
Epsom Salts, saturated solution[b]	**(Nos. 7, 8 and 9)** 0.00	**(Nos. 7, 8 and 9)** 0.00	0.00	0.00	0.00	0.10	0.00 Vari-colored	0.00	0.43	0.085	0.36	0.045	....	....	0.1 Slightly discolored	0.10
Developing solution containing "hypo" acetic acid, sodium sulfite, chrome-potash alum	**(Nos. 4 and 7)** 0.000	....	Badly attacked, deeply pitted 99.3	....	Badly tarnished not pitted 10.6	....	63.1	....	....	....	....	....	0.32	....	....	....
Borax Fusion, 1 hour at 1650° F	**(No. 7)** 40.9	**(No. 9)** 56.3	45.0	....	50.9	....	....	....	....	328.4	....	296.0	Tarnish	0.00	....	7.32
KCN fusion at 1650° F	**(No. 9)** See Note 1		See Note 2		....	....	....	....	....	....	....	....	....	....	....	....
Salicylic Acid, 40 cc. per test piece, 5 g. salicylic acid, 150 cc. pure grain alcohol, 300 cc. water, 20 hours	**(All Resistal Alloys)** 0.000	....	....	....	0.57	....	0.84	....	2.38	....	0.09	....	0.29	....	1.7	....

[a] Data is here given on Rezistal Alloys Nos. 4, 7, 8, 9 and 2600. The particular alloy in each test is represented by bold face figures.

[b] The runs at room temperature with this solution lasted 216 hours.

NOTE 1.—In covered "Rezistal" capsule 1.523 in. in inside diameter and 2.5 in. in depth, weighing 487 g. at start. Capsule filled half-full with 30 g. of 99-per-cent KCN (c. p.).

First fusion 1 hour........gained 1 g.
Second " 2 " ....no change
Third " 2 " ...." "
Fourth " 2 " ...." "

NOTE 2.—A piece of chromium iron weighing 8.4002 g. was put in the rezistal capsule and was subjected to KCN fusion for 1 to 2-hour periods. In the first fusion it gained 40 mg. and in the second it gained 9 mg., indicating high resistance.

Mr. Johnson. and at 90 to 100° C. The attack of molten salts is also being studied. The room temperature tests are of 24 hours' duration and the 90 to 100° C. tests of 2 hours' duration—these short times have been adopted because of the great extent of the program as at present outlined.

It is expected that the results will point the way to the selection of the most adaptable metal for any specific purpose and will be a reliable index of resistance to corrosion. As a basis for comparison, the following metals are being tested under the same conditions: 99-per-cent nickel, monel metal, chromel rod, sheet copper, Stainless steel, Stainless iron and 26 to 28-per-cent chromium-iron.

Approximately the same area is exposed to the same volume and dilution of the reagent in each group of tests. The results are reported in milligrams loss per square inch of exposed surface.

All of the results obtained to date are given in the accompanying table.

Mr. Graham. MR. W. F. GRAHAM[1] *(presented in written form)*.—The tabulation of data forming a part of this Symposium indicates a recognition of the fact that corrosion resistance of a metal or alloy is not the whole story. Selection of a material for a given purpose requires knowledge of its strength, the shape or size in which parts may be obtained commercially, the material's machining and grinding characteristics, and its comparative unit cost.

With these and other qualifications in view, there has been recently developed a series of alloys of the nickel-copper type known as "Everbrite" for use in service in which such alloys have application. This alloy is included in the committee's tabulation.

Nickel-copper alloys have desirable corrosion resistance in many respects. Primarily, however, they are alloys which exhibit good physical properties for non-ferrous materials, and fair machining properties.

The recent demand for high temperatures and pressures in the chemical and power plant field has given designing engineers great concern in obtaining materials of sufficient strength to withstand the stresses imposed on auxiliary equipment such as valves and fittings. Tension tests of "Everbrite" metal in many instances show a maximum strength of 100,000 lb. per sq. in., or better, and a yield point of 70,000 lb. per sq. in., or better, with an elongation of 25 per cent. The Brinell hardness averages 200. The machining is free and the material will lap or grind without piling up. This latter property is a very valuable one for a material to be used for valve seats. The alloy has been produced in forgings having an outside diameter of over 20 in.

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[1] Metallurgist, Curtis Bay Copper and Iron Works, Inc., Baltimore, Md.

Mr. Jones.

MR. JESSE L. JONES[1] (*presented in written form*).—Manganese bronze is one of the most important corrosion-resistant materials in use at the present time. Its value as an alloy for propeller blades has been proved by years of successful use. It is well known that sea water is an active electrolyte containing, as it does, notable quantities of sodium chloride, magnesium chloride, etc. Notwithstanding this fact, propeller blades and hubs which have been in use for many years are but little affected by sea water, the original marks of the saws, grinding wheels and other cleaning apparatus used in dressing the castings being as sharp and well-defined as before the castings were put in service.

The chief reason for the comparative immunity of manganese bronze from corrosion, notwithstanding its high zinc content, is presumably its great density. While it is true that castings of this alloy for pressure work have not proved entirely satisfactory, this is because of the tendency of alloys of this nature to form emulsions when in a molten state and to retain rather tenaciously particles of alumina and other oxides. Also, there is difficulty in a case of castings of uniform cross-section in securing satisfactory feeding when alloys of high shrinkage are used. In the case of propeller blades, however, the castings are of such large size that an opportunity is afforded for suspended impurities to rise to the surface of the casting, and as castings of this character are nearly always poured in a vertical position, porosity due to the difficulty of feeding is to a great extent avoided.

The specification for Built-up Propeller, adopted by the Marine Division of the Machinery Builders' Society, May 5, 1924, calls for manganese-bronze blades, but the hubs are made of gray iron including 25 to 35 per cent of steel scrap. It would be interesting to know whether the intent of this specification is only to cheapen the propeller, or also absolutely to safeguard the blades from possible corrosion and breakage when not operating under normal conditions in free water.

An interesting alloy of the manganese-bronze type is "Turbidium," made by Harlan & Wolf, Belfast. Desch gives its analysis as:

Copper	47	per cent
Zinc	46	"
Iron	1	"
Aluminum	2	"
Nickel	4	"

Other analyses show a similar composition, but are without the nickel. This material in small castings is said to consist entirely of

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[1] In Charge of Chemical and Experimental Laboratory, Material and Process Division, Westinghouse Electric and Manufacturing Co., Pittsburgh, Pa.

Mr. Jones. the beta constituent, to be resistant to both corrosion and erosion, and hence suitable for the propellers of destroyers, etc.

Manganese bronze has proved satisfactory for mining equipment, especially in the case of screen plates, which are made preferably from rolled manganese bronze.

Manganese bronze has also been used in the cast form for lifting frames for pickling sheet steel in dilute sulfuric acid. By making these frames, hooks and similar castings used for pickling of generous proportions, a service of several years is usually obtained.

Mr. Saklatwalla. MR. B. D. SAKLATWALLA[1] (*presented in written form*).—Mr. Armstrong has contributed very valuable data as to the historical development of high-chromium rustless steels and has brought together in the most admirable manner the different compositions that have been suggested in the past. However, like all of us mortals, he is not free from some sins of omission and commission.

Before going into detailed discussion of points so ably brought out by Mr. Armstrong, the writer would like to discuss the general possibilities as to future scope and applicability of the rustless alloys. Mr. Armstrong touches upon the question of price, which is undoubtedly the most important factor in the general development of this material. As long as the price of such material remains high, its application will be rather limited. For any appreciable tonnage production and wide engineering application of rustless iron, the price probably will have to be a fraction of the present-day prices. As Mr. Armstrong points out, especially in the case of the low-carbon metals, the high price is due to the price of carbon-free ferro-chromium used in its manufacture. Therefore, the future development of rustless metallurgy must lie with processes which do not require the use of this expensive ferro-chromium. The production of high-chromium steels directly from chrome ore has been worked out on the commercial scale, and steels made by this process can be marketed at only a fraction of the price of the material available at present.

Mr. Armstrong reviews the history of the development of high-chromium steels more or less from the phase of the patent situation and attaches importance to this phase. He has reference to the product or composition patents. As to the methods of manufacture of the material directly from chrome ores, which insures a wide and general economical application of the material for most purposes, the patent situation is more fortunate and clearer, especially in the United States. There has been considerable publicity given to the advancement of this art in Great Britain. As a matter of fact, however, the

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[1] General Superintendent, Vanadium Corporation of America, Bridgeville, Pa.

Mr. Saklatwalla.

issued patent in this country covering the basic idea of using chrome ore with silicon as a reducing agent is about ten years old and several subsequent patent applications for specific methods of carrying out the basic idea in this country carry a date of priority ahead of any of the English patents. These applications are still pending in the patent office.

Referring to the direct process in Mr. Armstrong's paper, quoting from the Bureau of Mines *Bulletin No. 6* of the Coal Mining Investigations, published by the Carnegie Institute of Technology, inference is made that the material manufactured by the direct process may be liable to have a greater number of oxide inclusions. This is contrary to actual experience. Steel produced by the direct process, rolled into sheets, and examined under the microscope has actually proved to be equally clean, if not more so, than that produced by the use of ferro-chromium. In the direct process, the ore is not thrown into the steel at haphazard but the incorporation of the oxide in the slag and of the reducing agent in the steel is carried out on a systematic basis. During the entire operation, the steel is throughly protected from absorption of oxides by the presence of an appreciable quantity of the reducing agent and the final removal of the reducing agent is accomplished only just before tapping. This protection through the presence of silicon during the entire life-history of the heat is not afforded when the chrome is introduced by means of ferro-chromium. The validity of this assumption has been perfectly proved by actual experience.

Mr. Armstrong alludes in his paper to an intermediate class of alloys, which, while not perfectly non-corrosive, are partially so. He alludes to a composition lower in chromium with nickel and silicon. Such partially rust-proof alloys, however, can be produced at a much less cost by the combination of an equally low chromium content with a very much lower copper content than the nickel specified. Such alloys are fairly rust-resisting, with a high degree of acid resistivity and are cheaply produced.

In the high-chromium steels, Mr. Armstrong advises the use of a silicon content. It is obvious that such a silicon content is useful for non-scaling properties at high temperatures. He further ascribes useful properties to the silicon content during the process of rolling, but he does not give us any data as to the influence of silicon on the non-corrosive properties at ordinary temperature of the finished steel. It is generally acknowledged that the high-chromium steels with a low carbon content are more resistive than those with a higher carbon content. Since silicon is in the same group of elements with carbon, would not silicon behave similarly? If that is the case we may be

Mr. Saklatwalla. acquiring the benefits in rolling at the expense of non-corrosive properties in the finished product. It is, therefore, important to conclusively prove by experimental evidence whether the presence of silicon affects the non-corrosive service of the material adversely or otherwise.

As to the addition of other elements such as titanium, zirconium, etc., it appears superfluous to add such elements. From various tests it appears to the writer that additions of other elements such as the above, or even manganese, while they may have a salutory effect as to the mechanical properties of the steel, are in no way desirable from the corrosion standpoint. The only exception to this seems to be copper, inasmuch as a content of copper seems to behave as a substitute for part of the chromium. It may seem, therefore, that a rustless iron, in which resistance to mineral acids is not desired, should consist of iron and chromium only and be as free from other elements, and have as low a carbon content as possible.

Mr. Armstrong's omission of copper among the elements is rather remarkably conspicuous, as in the experience of the writer copper seems to be the most useful non-corrosive element in conjunction with chromium.

Mr. Hall. MR. R. E. HALL[1] (*presented in written form*).—In a bulletin on "The Effect of Acidity and Oxygen on Corrosion of Metals and Alloys in Acid Mine Waters" (Coal Mining Investigations of the Carnegie Institute of Technology, Pittsburgh, Pa.), to be published soon, it is established that for metals below hydrogen in the electromotive series the acidity of the corroding solution within the limits met in mine waters is of little influence, but the concentration of ferric ion is the controlling factor on rate of corrosion. For metals above hydrogen, both acidity and ferric ion concentration function. The rôle of the ferric ion is that of making the potential oxygen concentration in the corroding medium very high, in fact, equivalent to that resulting from a pressure of some atmospheres of air.

For determining the value of a metal or alloy to be used in mine water, therefore, it seems advisable to determine its rate of loss in two types of synthesized corroding media. In one, the concentration of sulfuric acid is varied within the limits met in mine waters, and no ferric ion is present. In the other, the concentration of sulfuric acid is fixed (5000 p.p.m. is satisfactory) and the amount of ferric sulfate is varied.

Any type of mechanical device which will rotate either solution or metal sample is satisfactory for the experiment. Five or six hours is ample time for establishing the rates of loss. These rates, once estab-

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[1] Physical Chemist, U. S. Bureau of Mines, Pittsburgh, Pa.

Mr. Hall.

lished, are plotted against the concentration of H_2SO_4 and of $Fe_2(SO_4)_3$ or ferric ion. Finally, a survey of the mine water analyses covering a period of a year, if these are available, will allow one to judge of the corrosion rate in any particular mine by referring to the curves for the rate corresponding to the average acidity and ferric ion concentration in the mine water.

We have found an impressed electric current to be of no value in these determinations of rate. However, the use of the current for accelerating solution of non-homogeneous materials, so as to exaggerate any tendency toward pit formation, is of undoubted value.

Mr. Bassett.

MR. W. H. BASSETT[1] (*presented in written form*).—Considering some of the commercial alloys used for resistors at ordinary temperatures, extensive use is made of nickel silver of two varieties, usually in the form of annealed wire. One contains 18 per cent of nickel and has a circular mil-foot resistivity of approximately 189 ohms, and the other contains 30 per cent of nickel and has a circular mil-foot resistivity of approximately 290 ohms. The nickel silvers have a somewhat higher temperature coefficient and thermal electromotive force against copper than other alloys to be described later, but they find use in rather considerable quantities for general resistance work where these characteristics are relatively unessential and lower cost is of greater importance. For continuous operation at temperatures much above 100° C., nickel silvers are not recommended.

TABLE II.—COMPOSITION AND PHYSICAL PROPERTIES OF NICKEL SILVER AND MANGANIN.

Name of Alloy	Chemical Composition, per cent					Resistivity		Temperature Coefficient per 1° C. (15–30° C.)	Thermal E.M.F. against Copper, microvolts per 1° C. (0–100° C.)	Tensile Strength, lb. per sq. in. (Annealed)	Elongation in 2 in., per cent (Annealed)	Density, g. per cu. cm..	Melting Point, deg. Cent.
	Cu	Ni	Mn	Zn	Fe	Circular mil-foot ohms	Cm., microhms						
Nickel Silver, 18 per cent	55	18	..	27	..	189	31.4	0.00033	15	65 000	40	8.68	1030
Nickel Silver, 30 per cent	47	30	..	23	..	290	48.2	0.00034	21	75 000	35	8.74	1160
Manganin I...........	84	..	15	..	1	300	50	0.000020	1.0	70 000	30	....	950[a]
Manganin II...........	85	4	11	..	..	250	41.7	0.000020	1.0	72 000	30	....	1050

[a] Zemczuzny, Urason, Rykowskow, "Cooling Curve on Copper-Manganese," *Metallurgie*, VI, 332.

For the most exacting requirements, such as for precision apparatus and measuring instruments, alloys commonly known as manganin are used, either in the form of ribbon or as wire. Until a few years ago, practically all of the resistance material of this class came from

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[1] Technical Superintendent, American Brass Co., Waterbury, Conn.

Mr. Bassett. abroad, but at the present time the manganin produced in this country is superior to the foreign product formerly obtained. Results of experiments on manganin were published by Bash,[1] and also by Hunter and Bacon[2] in 1919.

Two types of manganin are commercially produced. The first is an alloy of 85 per cent copper, 14 per cent manganese, and 1 per cent or less of iron. In the second alloy, 4 per cent of the manganese is replaced by nickel. The circular mil-foot resistivity of the former is approximately 300 ohms and of the latter 250 ohms.

Both have an extremely low thermal coefficient of resistivity and thermal electromotive force against copper which makes them especially adapted for precision requirements. It is a characteristic of manganin that the temperature-resistance curve is not a straight line, but has a peak, the position of which varies with the composition of the sample.

The properties of manganin are somewhat sensitive to the treatment given the metal in production. Care must be observed in annealing to prevent oxidation of the surface, as manganese is selectively oxidized which produces a coating of copper and results in a higher temperature coefficient. The pickling of the annealed metal must be carried out so that no selective action results, which would likewise seriously affect the temperature coefficient.

The temperature range throughout which manganin is useful is the same as that for nickel silver. When it is used under exposed conditions it should be covered with a protective wrapping or coating to prevent oxidation of the surface.

The accompanying Table II gives the chemical composition and the physical properties of the nickel silver and manganin alloys which have been described.

Mr. Mathews. MR. JOHN A. MATHEWS.[3]—These papers open up an entirely new field of metallurgy. We are getting into materials and properties diametrically opposite to those with which we have been familiar in other classes of steel. For instance, certain high-chromium-nickel steels, instead of getting more brittle as the quenching temperature increases, become progressively tougher and more ductile, and, on the other hand, they become progressively tougher as they are cooled. Langenberg, at the Watertown Arsenal, has shown one of these steels to increase progressively in its shock resistance when it is cooled down to −80° F.; whereas the ordinary steel is more or less embrittled at 0° F. and below.

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[1] *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. LXIV, p. 261 (1919).

[2] *Transactions*, Am. Electrochemical Soc., Vol. XXXVI, p. 323 (1919).

[3] Vice-President and Metallurgist, Crucible Steel Co. of America, New York City.

So we must get used to some new ideas about steels. It was shown that no one steel answers all purposes; we must learn which steel is suitable for a specific purpose, and use it accordingly. The steels discussed by C. M. Johnson here, probably present the widest field of usefulness both as regards corrosive agents and resistance to oxidation at elevated temperatures. **Mr. Mathews.**

MR. H. J. FRENCH.[1]—I should like to say a few words despite the fact that I am in danger of repeating some of the remarks made at the Cleveland Symposium on heat-resisting alloys.[2] I am inclined to believe that Mr. Fahrenwald takes an exceedingly pessimistic view both with respect to our present state of knowledge of and the future development in materials for high-temperature service. I gained the impression that he limited future developments to the nickel-chromium-iron alloy series with possibly cobalt, tungsten and one or two other additions. Such an opinion, of course, is extremely hazardous in view of the metallurgical history in this and other countries. Mr. Fahrenwald also appears to be rather pessimistic regarding the instability of ordinary or special alloy steels, both in the heat-treated and so-called "work hardened" conditions. Many examples could be cited where such materials have given very satisfactory service at relatively high temperatures. **Mr. French.**

There is also one point with respect to the properties af chromium-iron-carbon alloys which should be mentioned. At given temperatures in the range of 1200 to 2200° F., relatively small differences are observed in mechanical properties in high-chromium (stainless) steels with or without small additions of other special elements, according to published or available data. However, such additions may materially affect the chemical stability.

There is another feature of great importance, and that is whether consistently uniform properties can be produced commercially in nickel-chromium-iron or other alloys for high-temperature service. Here we are rather fortunate, at least in one respect, for the softening effects of very high temperatures tend to counterbalance initial differences in casting practice and minor differences in chemical composition due to segegration or other causes. However, the ability to consistently and uniformly produce definite physical and chemical performances is an item of the greatest importance and I do not remember that it was mentioned or at least sufficiently emphasized by the speakers this evening.

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[1] Physicist (metallurgy), U. S. Bureau of Standards, Washington, D. C.

[2] See page 9.

Mr. Waddington.

MR. W. H. WADDINGTON.[1]—I am rather sorry that Mr. Anderson and Mr. Enos are not here to present their paper on acid mine water corrosion. However, reference has been made this afternoon to *Bulletin No. 6* of the Bureau of Mines, which covers the accelerated electrolytic tests. There are certain conclusions they have come to in a broad way in that paper that I do not think are exactly in keeping with the facts. For example, in the simple tests the high-chromium steels and the chromium-nickel-silicon steels showed a very low loss by corrosion. In the accelerated tests they showed a rather high loss. There are two steels, with 18 and 13 per cent chromium, that were not included in the simple tests but were in the accelerated electrolytic tests, where they showed practically no loss whatever. Now these steels—particularly the latter, which is really stainless steel—have been given very careful and extended tests under actual service conditions, and I think that mine men who are familiar with their applications know that stainless steel under mine water service conditions does not stand up. In other words, certain conclusions regarding the value of accelerated tests as compared to long-time tests are not definite and are not as conclusive as they might appear to be.

Mr. J. Strauss.

MR. JEROME STRAUSS.[2]—In referring to Mr. Hultgren's paper, it may be of interest to recall again that his tests were of short duration. They were also continuous. Long-time tests intermittently operated might have yielded results, in so far as rusting is concerned, that were entirely different. Another point is that presumably the heat treatments used were those recommended by the manufacturers at the time at which these tests were made. Recent investigations of high-chromium steels have caused marked changes in recommended heat treatment practice and it is possible that the recommended heat treatments used no longer apply. Presumably the test loads were such that the steels were stressed very close to their ultimate compressive strength; these high-chromium steels all have low proportional limits but this proportional limit is adjustable over a rather wide range by heat treatment modification and it is therefore possible that by such modification Mr. Hultgren's steels might have shown greater endurance and also that the differences in endurance of these three steels might have been much less. Although the quenching temperature has a pronounced effect, the main factor, when considering the present tests, is the employment of a tempering temperature of 250° C. None of the steels which I have used in my own tests have a proportional limit after such tempering which is not lower than that

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[1] Driver-Harris Co., Harrison, N. J.

[2] Material Engineer, U. S. Naval Gun Factory, Washington, D. C.

Mr. J. Strauss.

obtained by some higher tempering temperature. These facts must be borne in mind in interpreting the results of Mr. Hultgren's work.

In connection with the remarks of Mr. Jones, I wonder whether manganese bronze has not found its way into propeller blades largely because of its price? There are other bronzes, and in particular aluminum bronze, which would meet the requirements of this service exceptionally well; but they have to be manufactured largely from new metal, whereas satisfactory manganese bronze can be produced from scrap metal and it is therefore cheaper.

Mr. Gillette.

MR. C. S. GILLETTE.[1]—I have listened with considerable interest to the material brought out by this Symposium, but it seems that one of the most important applications of rust-resisting alloys has not been touched upon. I refer to the application of these alloys in the manufacture of turbine blading. Such application is of great interest to the Bureau of Engineering of the Navy Department which I represent. Turbine blading has always presented a serious problem and a problem which has never been satisfactorily solved. Corrosion resistance, erosion resistence, high tensile strength, high elastic limit, high endurance limit under alternating stresses, good elongation and impact resistance are all extremely important features in turbine blading. The experiments which Mr. McAdam has discussed this morning were initiated primarily to obtain data and information relative to the suitability of the rust-resisting alloy steels to turbine blading. It seems at the present time that the corrosion-resisting steels can be very satisfactorily applied for such purpose. European practice has already adopted such practice quite extensively. I trust that manufacturers will appreciate the possibilities in this connection and that it soon will be possible to obtain consistent results on corrosion-resisting alloy steels sufficient to justify their use for this most important application.

Mr. Armstrong.

MR. P. A. E. ARMSTRONG.[2]—The paper by Messrs. Johnson and Christiansen on automotive valves was, I think, a little unfair to chromium and silicon, though he was very fair in the case of cobalt chromium containing 18 per cent of alloy and 1.5 per cent of carbon. The chromium and silicon contained about 12 per cent of alloy and 0.50 per cent of carbon. Apparently the alloy percentage was not based on quality but on price, and there could have been used chromium and silicon materials that would have solved the trick better than the chromium and silicon he used. It wore out because it was not hard enough. The material containing cobalt was successful from

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[1] Lieutenant-Commander, United States Navy, Washington, D. C.

[2] Vice-President, Ludlum Steel Co., Watervliet, N. Y.

Mr. Armstrong. the wearing point of view because it contained very high carbon. I take this opportunity of making a suggestion to Mr. Johnson in his further trials, that he use higher carbon in his chromium-silicon alloy steel.

Mr. French. MR. FRENCH.—I notice in looking over the very valuable tables appearing in the Introduction that there are quite a number of blank spaces for tensile properties at high temperatures. It so happens that I have recently made tests on a number of the alloys discussed here this afternoon, and if it is the desire of the Committee on Arrangements and the Society, I shall be glad to turn over to them the results of these tests. I have in mind particularly two of the high nickel-chromium-iron alloys, the chromium-copper steel and the alloy mentioned by Mr. Price.

[ED. NOTE.—These tests are included in Table II of the Introduction—Calite "A" and "B," Carpenter Rustless and Admiralty Nickel.]

Mr. Knerr. MR. H. C. KNERR.[1]—Mr. Fahrenwald, in his very interesting paper, discussed the physical properties of some of these alloys at high temperatures under continued stress. I should like to ask whether he can give any information in regard to the possible effects of the grain growth in causing deterioration of those physical properties after prolonged heating.

Mr. Palmer. MR. FRANK R. PALMER[2] *(by letter)*.—When Stainless steel was first introduced into this country it was known only in the tempering grade containing approximately 0.30 per cent of carbon and 13.00 per cent of chromium. Other types of steel with stainless properties had been described to some extent in the technical literature, but this was the only form commercially available and its use had been limited largely to table cutlery. This cutlery steel possesses some non-corrosive properties in the annealed or softened condition, but it is only by proper hardening and subsequent polishing that maximum corrosion resistance is realized. It soon became evident that this steel was limited to a relatively narrow field by reason of the fact that hardening was necessary in order to make it rust-proof. There are a great many manufactured parts in which non-corrosive properties are essential where heat treatment is unnecessary and undesirable, and where a final polishing is not at all practical. To date, the search for a material to fill these needs has been productive of three types of rust-resisting steel which are recommended for use in the unhardened condition.

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[1] Metallurgist, Naval Aircraft Factory, Navy Yard, Philadelphia, Pa.

[2] The Carpenter Steel Co., Reading, Pa.

Mr. Palmer. In order to appreciate the properties and peculiarities of these three new types, it is necessary to review briefly some of the facts that are known regarding simple high-chromium steels. Forgetting for a moment the influence of carbon, the addition of chromium to iron progressively increases the resistance of the latter to atmospheric, chemical and high-temperature corrosion. The useful effect of chromium is first observed at about 6 or 7 per cent, and the iron becomes increasingly more non-corrosive as the chromium increases up to above 20 per cent, this being approximately the limit in most of the malleable non-corrosive steels now in use. Corrosion of steel is usually the result of two actions—the solution of iron itself and the electrolytic action between the iron matrix and the carbide globules which are imbedded in it. The presence of relatively large amounts of chromium in the iron serve to reduce or entirely prevent the solution of iron in water and many other corrosive reagents, but as soon as appreciable amounts of carbon are introduced, this condition is modified. When the free carbides are completely dissolved by heat treatment, their effect is no longer evident, and the steel becomes stainless. It is for this reason that Stainless cutlery steel requires hardening. There are two general methods of eliminating this electrolytic corrosive action and out of these two methods have developed the three types of rust-proof machinery steels mentioned above.

The most obvious method is to eliminate the carbon. This has been done in the so-called Stainless irons which contain about 12 to 14 per cent chromium and as little carbon as possible, usually less than 0.12 per cent. While this type of material is more non-corrosive in its softened condition than the regular Stainless steel containing higher carbon, the fact that it does contain a small percentage of carbides limits its successful application to the milder corrosive agents. Such steels are highly rust resisting but are not literally rust-proof.

The second general method consists in the addition of certain elements which tend to reduce the potential difference between the matrix and its carbides. The matrix of the standard Stainless steel is electro-positive to the carbides, and therefore suffers by electrolytic action.

Nickel is slightly electro-negative to iron and if sufficient of this element is added it seems to accomplish the desired results. The fact that nickel must be added in large quantities (usually above 15 per cent) brings about a condition which throws the nickel-chromium non-corrosive steels into a class by themselves. Large additions of nickel cause the steel to become austenitic so that while these products

Mr. Palmer. are referred to as "soft," they are not, in the strict sense of the term "annealed." It is entirely likely that the austenitic matrix assists considerably in making these steels non-corrosive. The austenitic nickel-chromium steels may contain up to about 0.50 per cent of carbon and those which the writer has examined or experimented with usually contain considerable undissolved carbide. These steels are only truly rust-proof when the nickel and chromium are added in the proper proportions and in the proper quantities. It appears necessary to have the chromium as high or higher than in the orthodox Stainless steels and almost twice as much nickel in order to secure maximum non-corrosive properties. Steels of this class manifest all of the properties with which we are familiar in austenitic steels—they are extremely tough, non-magnetic, difficult to machine, and have a relatively low elastic ratio. It is obvious that they will not respond to hardening.

Chromium in itself is electro-negative to iron and, by holding the carbon constant at about 0.30 per cent, it is possible by adding more chromium to the standard Stainless steel to greatly reduce the potential difference between the matrix and its carbides. Perhaps the most active electro-negative element available is copper and by increasing the chromium content to about 20 per cent and then adding a small percentage of copper (about 1.00 per cent) it is possible to secure a rust-proof steel which fulfils all of the requirements without becoming austenitic.

A steel of this type can be annealed to the usual pearlitic form and in spite of its carbides is more non-corrosive than the regular Stainless steel even when the latter is properly hardened and polished. This same analysis was one of the two described by Strauss and Talley in the paper "Stainless Steels: Their Heat Treatment and Resistance to Sea-Water Corrosion" as being usually immune to the action of salt-water spray. The beneficial effect of copper was also pointed out by Mr. Saklatwalla in the discussion of Mr. Armstrong's paper. The unique properties and general utility of this class of steel warrants a further description.

Being pearlitic, this chromium-copper steel (C, 0.30 per cent; Cr, 20.0 per cent; Cu, 1.0 per cent) is magnetic and is freely and easily machineable. The steel may be handled in automatic screw machinery without any special precautions and can be held on magnetic chucks for grinding. This type of steel may be regarded as rust-proof machinery steel; it does not harden when heat treated, and is, therefore, used in exactly the same manner and for the same type of work as ordinary machinery steel. It has, however, obvious advantages over the latter material.

Mr. Palmer. The chromium-copper steel is entirely immune to atmospheric and fresh-water corrosion. In the writer's experience it is not even tarnished by sea water and this is substantiated in the main by Mr. Strauss' work. Reference to the tabulated data in the Introduction shows that the chromium-copper steel is attacked by sulfuric acid. This is true only when a small quantity of sulfurous acid is present and as this trace of sulfurous acid is eliminated by the presence of any oxidizing agent and by most metallic salts, the chromium-copper steel is immune to many types of sulfuric acid in technical use. The presence of a very small quantity of ferric, cupric, chromic, manganic and other metallic salts renders sulfuric acid non-corrosive to this steel and it will remain bright indefinitely. Dry sulfurous acid gas such as is used in refrigerating apparatus has no effect upon the steel. It is also immune to the combustion products of smokeless powder, and gun barrels made from it will never rust regardless of whether they are cleaned after use or not.

The chromium-copper steel shows the same conspicuous resistance to oxidation at high temperatures as it shows to chemical corrosion. The writer's observations substantiate in general those of MacQuigg, who has pointed out in his paper the superiority of steels containing upwards of 20 per cent of chromium over those containing more moderate percentages of this element when subjected to furnace gases at extremely high temperatures.

MacQuigg has pointed out the difficulty in securing laboratory data regarding the speed with which scale forms at elevated temperatures. Owing to the difficulty in completely removing the scale after the test, in order to weigh or measure the sample, the writer has adopted a procedure in which the sample is placed in an ignited porcelain crucible and carefully weighed. The crucible is then placed in an electric muffle furnace, heated to the desired temperature, and air or other gases are permitted to pass freely over the sample during the run. When the run is complete, the crucible is removed and cooled in a desiccator and reweighed. Oxidation is of course recorded as weight increase. These results are, naturally, valuable only when compared with similar results obtained in the same way, but the extreme resistance of the high chromium-copper steel may be realized by the fact that the weight increase at 800° C. amounts to less than 0.00003 g. per square centimeter per hour. This represents simply a yellow tarnish after an eight- or ten-hour run. By slightly altering the annealing practice, the proportional limit can be increased by 45 to 50 per cent above the figures given in the tables of the Introduction with corresponding decrease in ductility.

Mr. Palmer. The coefficient of thermal expansion is almost exactly the same as for ordinary steel and this fact has simplified considerably the use of this product for non-corrosive trimming of cast or forged steel parts. One of the chief objections to the use of non-ferrous metals in trimming valves and similar equipment is the wide difference in the coefficient of expansion between the different metals.

Since the chromium-copper type of steel is magnetic it yields a hysteresis curve of the usual form. A magnetizing force of 300 gilberts per centimeter produces an induction of 14,540 gausses; the residual induction is 9500 gausses, and the coercive force required is 7 gilberts per centimeter.

The importance of these various types of non-corrosive machinery steels which do not require hardening can scarcely be over-emphasized as it does not require the gift of prophecy to foresee that by far the largest application of corrosion-resistant alloys lies in directions where an unhardened material will be used.

Mr. Malcolm. MR. V. T. MALCOLM[1] (*by letter*).—There has been considerable discussion as to the merits of various alloys in their resistance to the corrosive action of liquids and gases. It occurs to the writer that the corrosion-resistant properties depend to a great extent on the physical structure of an alloy and that a knowledge of the internal composition is necessary in studying its corrosion resistance. Particularly is this true in the case of casting alloys. Many failures of alloy castings are due to improper pouring temperature, soaking time or other details of foundry or mill practice.

The chemical composition of an alloy tells us nothing regarding the alloy's ability to withstand corrosion, for the chemical composition gives no indication as to the distribution of the constituents, the presence of foreign inclusions, shrinkage cavities, or of the size of crystals. When a pure metal solidifies it is obvious that the resulting solid must be chemically homogeneous. Any lack of homogeneity can only be due to the formation of shrinkage cavities during solidification or to the presence of dissolved gases. As a metal solidifies, crystallization takes place, the form and size of the crystals depending upon the kind of metal and the rate of solidification. In nickel-copper alloys the crystals grow inward from the cooling surfaces into the interior which is still molten, the main branches throwing out arms. The liquid mass freezing between these branches forms a large feathery outline known as a dendritic structure. Nickel-copper alloys form homogeneous mixtures in the solid state or what are commonly known as solid solutions. In solidification each of the crystals which is formed ultimately attains the same average composition as the molten liquid from which it was deposited. **Mr. Malcolm.**

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[1] Metallurgist, Chapman Valve Manufacturing Co., Indian Orchard, Mass.

In some cases, however, complete homogeneity is not attained by solid solutions because of the rate of cooling. The characteristic feature of the structure in such a case is that the arms of the dendrite are ill defined and may readily be seen under the microscope. If the solution is cooled slowly, the entire solid will have a uniform composition, and a mass of homogeneous crystals will result. But when the cooling has not been sufficiently retarded, each of the crystals will consist of one of the metals relatively poor in the other constituents. This selective method of freezing results in a cored appearance as seen under the microscope. In nickel-copper alloys the crystals which separate out first are richer in nickel than those which separate later. There is thus a gradual decrease, in the case of a moderately rapid rate of cooling, in the proportion of nickel from the center of each crystal to the outside.

Another difficulty in the manufacture of alloys rich in nickel lies in their absorption of carbon monoxide gas and in their ability to be readily oxidized. A knowledge of the causes and the control of oxidation is necessary to successfully work with these alloys. The constituent metals of a nickel-copper alloy are capable of producing, absorbing, dissolving or alloying with a considerable amount of their own oxides, and unless great care is used in the melting and casting operations the product will be found to be honeycombed and spongy.

There is a popular misconception that nickel-copper alloys resemble ordinary bronze in their characteristics. However, these alloys are quite individual and have a number of special characteristics to the extent that they resemble steel more than bronze in casting.

Summing up, it is found that in good practice sound castings or ingots can be obtained from most mixtures, provided, first, that there are no reactions which lead to the formation of gases and that there is no extensive tendency towards segregation, and second, that the shrinkage is properly taken care of. There is a difference in temperature between the outside and the interior of an alloy that is being cooled, as a result of which crystallization begins at the outside and is completed near or somewhat above the center of the mass. The difference in density of crystals and liquid may indirectly cause porosity. Microscopic examination reveals the existence of voids and shrinkage cavities due to the metal having been poured out at an incorrect temperature, the metal not being fluid enough to clean itself.

Mr. Lessells.

MR. J. M. LESSELLS[1] (*by letter*).—With reference to the paper by Mr. Fahrenwald, it appears from his consideration that there is no such thing as elastic properties of steels at high temperature, since he emphasizes only the strength properties. This, of course, is an entirely wrong attitude to take, since if precision instruments be used it is well known that elastic properties such as proportional limit and modulus of elasticity can persist for as high temperatures as 500° C. if the material be medium-carbon steel.

Another point is his pessimism regarding heat-treated steels at high temperatures. If the working temperature be less than the temperature at which the material has been drawn back, then there should be no danger. It appears that the author inferred otherwise. In a word, it seems that by forgetting about the elastic properties of the material an entirely wrong atmosphere is being created since it is on the basis of such properties that all true designs must be made.

The second point is with regard to thermal stresses. He waves aside the mathematician as if such analysis were unnecessary and of no value. Again the writer entirely disagrees with the author, because no results on such a complex subject will ever be forthcoming from experiment alone. It is only by a combination of experiment and analysis that a true picture can ultimately be found.

The writer has found the paper by Mr. McAdam very interesting. The fact that the endurance limit in bending becomes higher than the proportional limit in tension has been confirmed by the author's work on stainless steels. No attempt is made in the paper, however, to explain why this is so.

The remarks relative to the deflection method not being a reliable test for all kinds of steel and non-ferrous metals are not new, since this has already been discussed by the writer.[2]

Looking at the tension test curves for steel A we find the effect of the higher annealing temperature is to so change the form of the diagram in that the proportional limit is brought nearer to the yield point. If the yield point be taken as that stress corresponding to 0.0005 in. extension the ratio of yield point to proportional limit for the heat-treated steels becomes 2.2, 3.8, 1.4 and 1.4 respectively. The corresponding ratio of endurance limit to ultimate strength being 0.44 0.478, 0.56 and 0.54, respectively, indicates that the elastic properties have also a bearing on those of fatigue, and it appears that no clear understanding of the mechanism of fatigue will be complete unless these points be considered.

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[1] Mechanical Engineer, Research Department, Westinghouse Electric and Manufacturing Co. East Pittsburgh, Pa.

[2] *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 122 (1923).

Mr. Lessells.

The author mentions the fact that corrosion-resistant steels in the heat-treated condition show a higher ratio of endurance limit to ultimate strength than in the annealed condition, but this appears to be true in general for all steels in greater or less degree and appears to be a question solely of microstructure.

In general, the presentation of such a mass of experimental data may in itself be valuable to the designer, but since there are many points brought out and very little discussion made as to the underlying causes it may be pertinent to state that such data does not appear to be sufficient if the work is to have its true value.

Mr. B. Strauss.

MR. B. STRAUSS[1] (*by letter*).—It is true that the British Pasel patents originated with me. Pasel was an employé of the Krupp Co. in Essen.

However, the statement that Pasel had difficulty in obtaining British patent 13,415 in the year 1913, is not correct. And it is also incorrect that Pasel took out (or filed) a disclaimer covering the knowledge of the resistance of these alloys to concentrated acids or exceptionally strong acids. Through my researches, it was established for the first time that the chromium-nickel steels possess a very great ability to resist acids, particularly nitric acid. Further, I have already stated in my paper, that among the binary chromium steels, the chromium-nickel compositions are far superior by reason of their strength properties.

Mr. Armstrong.

MR. P. A. E. ARMSTRONG (*Author's closure, by letter*).—Replying to Mr. Saklatwalla, the reason I devoted no space to the methods of manufacture of high-chromium low-carbon alloys is because it really has nothing at all to do with the phase of the subject that I intended to cover. I included a reference to the production of chrome oxide in the furnace by silicon or aluminum, using the so-called direct method of manufacture, because my experience had shown that the manufacture of high-chromium low-carbon alloys by the direct method was far from satisfactory. Without question, it can be done; I have made many tons of the material by that method. Some of the earlier heats were made in 1919 and in the Armstrong patent No. 1,322,511 this method of manufacture is disclosed. I have used ferro-silicon, silicon, and aluminum as reducing agents, using chrome ore and chromium oxide separately and combined, with results that have always been about the same. If aluminum is used as a reducing agent in a basic-lined electric furnace, the amount of slag produced becomes so unwieldy as to make it difficult to correctly manipulate the furnace. It is difficult to get a higher chromium content in the finished melt than about 12 per cent. The chrome ore loss is very great, so that from the point of view of cost the direct process of manufacture is

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[1] Fried. Krupp, A. G., Essen, Germany.

Mr. Armstrong. apparently no more economical than the manufacture of low-carbon ferro-chromium and its subsequent use as a direct charge in the molten metal. If an acid-lined furnace is used, it is practically impossible to control the carbon content by reducing the chrome ore directly in the furnace. Silicon seems to behave a little better than aluminum from the point of view of slag if an acid-lined furnace is used. If a basic-lined furnace is used, the slag rich with silicon cuts the lining to such an extent that it becomes expensive and it may actually go through the lining of the furnace. One heat was lost because of cutting which entailed quite expensive repairs to the furnace.

Microscopic examination of finished bars has always shown them to be rich in inclusions which look like oxide—small round dots at the grain boundaries, in much the same way as oxides appear in copper. The steel seams very badly and contains a large number of internal cracks. The ingots are likely to be full of holes, and as the high-chromium alloy is non-welding, the ingots are worthless.

It is true that a reducing slag is used throughout and therefore it is fair to suppose that the steel should be free from oxide in any form. But it is also fair to say that the hot metal associated with the oxides and a reducing agent can absorb oxygen from the slag, either during the period that each particle of oxide is reduced, or from the oxide itself. The bath is reducing in that it is ready to take up oxygen. I should not like to say that molten iron and chromium are capable of reducing chromium oxide; but there is always a fair amount of silicon in the metal if a silicon reducing agent is used or a fair amount of aluminum in the metal if an aluminum reducing agent is used. Then again, carbon is always present so that the molten metal itself is a reducing agent and is capable of reducing chromium oxide. The oxygen liberated from the chrome ore or chromium oxide used may pass into solution in the molten metal.

My experience has shown that it is impossible to degasify a high-chromium iron low in carbon. If the metal is frozen quickly the oxygen is not liberated and the ingot, particularly a test ingot, is sound but weak. If the ingot is cooled fairly slowly, the chrome iron seems to have less ability to hold the oxygen in solution and gives it up as it passes from the liquid to the solid state. The larger the ingot made by the direct process, the more porous is the metal. Four-inch ingots can be poured fairly satisfactorily, the only trouble seeming to be with mechanical inclusions. With 7-in. ingots, some are full of holes and others are not so badly affected, due to the different rates of cooling and whether or not the ingot was poured from the beginning of the ladle or later. With 12 and 24-in. ingots I have not

Mr. Armstrong.

yet seen one free from holes. I find that my friends who have tried the same system report just about the same results, although they may differ in their opinion as to the cause.

Just what reactions take place in the furnace is a supposition based upon a certain amount of fact. Nobody knows definitely just what happens. This statement may bring forth a considerable amount of criticism but as a general statement I believe it is correct.

Under these circumstances and from the results that I have obtained to date I do not believe that the direct method of manufacture of high-chromium low-carbon chromium alloys is practical or even desirable. It would however, be quite unwise to be at all prejudiced. The metallurgical field and the art of melting as regards alloy irons and steels change so quickly and we learn so much each day that to have biased ideas would be extremely absurd.

Mr. Saklatwalla makes a statement that, to me, is remarkable. He draws attention to the fact that carbon and silicon are of the same chemical group and may therefore behave similarly. So are titanium, germanium, zirconium, tin, cerium, lead and thorium. Is it fair to believe that all of these metals have similar properties in iron as carbon? I think not. Is not Mr. Saklatwalla familiar with the fact that high-silicon iron is an acid-resisting iron? A 14-per-cent silicon iron is so well known in the chemical industry as to require no description here, yet white cast iron does not have properties similar to a high-silicon iron so far as chemical attack is concerned. The similarity between high-silicon iron and white cast iron is evident but only from the point of view of brittleness.

Carbon forms carbides with iron. Silicon forms a silicide which is a chemical compound. The difference is mechanical; silicon will enter into solution with iron up to about 20 per cent before any free definite chemical compound is discernible; that is, the chemical compound is formed and is dissolved in the iron. Iron and carbon form definite carbides which are not readily dissolved or held in solution; therefore the carbon, besides having but slight acid resistance, actually assists corrosion by causing differences in potential. Iron silicides will dissolve in iron and they require no heat treatment to hold them in solution. When they are dissolved in iron, the alloy has great resistance to mineral acid; therefore, there is no relation between these two elements dissolved in iron from that point of view.

Silicon and chromium form silicides which are just as soluble in iron as iron silicides; therefore, a silicon chromium exists in iron as a dissolved chemical compound. If silicon and iron form one of the finest alloys developed for resistance to acid attack, why should this

Mr. Armstrong. property be changed when chromium is alloyed with them? We should expect to find a high-chromium iron rich in silicon having properties akin to those that are present in an alloy rich in chromium and rich in silicon. This is shown to be a fact. High-chromium alloy of moderate carbon content will resist acid attack to a certain definite degree. If a high silicon content is added to the alloy having the same chromium and same carbon content, the alloy immediately becomes more resistant to sulfuric acid and hydrochloric acid, to which two acids chromium and iron are but slightly resistant.

Mr. Saklatwalla admits that silicon and iron with chromium is extremely scale-resisting to high temperatures and agrees that the silicon content is directly responsible for this. This is a proven fact. Surely resistance to oxidation at high temperatures calls for greater resistance to oxidation than at atmospheric temperatures.

As far as atmospheric rust-resisting properties are concerned, an alloy of, say, carbon 0.20 per cent, chromium 10 per cent, with a high percentage of silicon, 5 per cent by weight, will remain bright in the annealed condition for years without any signs of rust, whereas a similar alloy without the silicon and in the annealed condition will rust speedily. With an alloy containing less than 0.10 per cent of carbon, chromium about 17 per cent and silicon 1.5 per cent or higher, the alloy is decidedly more rust-resisting than would be a similar alloy low in silicon. Further, serious pitting so prevalent in chromium and nickel-chromium alloy is not present.

The higher the silicon content the more rust and pit-resisting the surface becomes and the more it is free from discoloration. I believe that the reason for this is that the protecting film that is formed upon the surface of the alloy is thinner and far less porous—probably not porous at all. The film is invisible and of no substantial color, and the underlying surface is fully protected from rust.

Silicon-chromium-iron alloys do not usually have 20 and 30 per cent of silicon because of the mechanical difficulties. The alloy will be brittle but from the point of view of rust resistance it will be advantageous to use silicon to such a high content. If Mr. Saklatwalla's fears were substantiated, then the high-chromium-iron alloy with high silicon content would rust just about as badly as ordinary iron. I believe that Mr. Saklatwalla knows that this is not a fact. I feel sure that he would freely admit that he would not expect it to rust. Therefore I am at a loss to know why he should have thrown out a suggestion that probably silicon acts like carbon and actually accelerates rust.

I quite agree that silicon and carbon are similar so far as increased

Mr. Armstrong.

physical properties are concerned, in fact we depend upon the silicon to impart to the alloy physical properties that cannot be obtained in an annealed high-chromium-iron. The silicon gives to the alloy what I have described as a metalloidal temper.

I did not mention copper as an addition that might be made to chromium iron, as contrary to Mr. Saklatwalla's statements I find that copper does not impart any marked properties to a high-chromium-iron alloy advantageous from the point of view of acid or rust-resistance. If copper, 2 per cent we will say, is added to a 16 or 17-per-cent chromium iron and the sample is tested with sulfuric acid by having the acid placed upon its surface, when the acid has dried up, the surface has the distinctive mark of copper sulfate and is more discolored than a similar alloy free from copper. If the test is conducted by immersing the sample in the acid so that there is no acid line, then the sample is affected just about the same way as is the straight chromium alloy.

The effects of hydrochloric acid upon a copper-bearing high-chromium alloy and upon one without copper are not markedly different. If anything, hydrochloric acid seems to have a greater attack on the alloy containing copper. Mr. Saklatwalla's contribution before other societies on copper-bearing high-chromium alloys has been very interesting to me, but the results that he obtained do not equal the results I have obtained. It is true my method of testing was a little different, but I have always conducted my experiments with the sample partly in acid and partly out so as to get the effect of the atmospheric line, or else with the acid put upon the surface and allowed to dry.

My experiments with copper and high-chromium alloys date back to 1917 and I find that the copper-bearing high-chromium alloy is not free from the objections common to high-chromium-iron alloys, namely, of seaming badly. Copper does not seem to add anything desirable to the high-chromium-iron alloy, as far as rolling, acid and rust-resistance are concerned.

Mr. Saklatwalla recognizes the excellent properties imparted to chromium-iron alloy by silicon in that they are easily worked. It was stated at the meeting that the successful manufacture of these alloys was a point not to be overlooked and that the steel maker must have a commercially workable metal if his production is to be on the same scale as with iron. I believe that in the silicon-chromium-iron alloy we have a very excellent solution to the commercial production of a rustless iron, although perhaps not the only one that will be produced as time goes by. It is my sincere belief that still undiscovered

Mr. Armstrong. alloys will be found to function in those fields of application not covered by silicon-chromium-iron or chromium-iron alloys.

Referring to the remarks of Mr. Benno Strauss, I think that he would have every right to criticize me if I had said that Pasel had had difficulty in obtaining British Patent No. 13,415 of 1913. I did not say this but merely said "apparently" and I did so because of the number of statements in the aforementioned patent which I will refer to again in dealing with the balance of his criticism.

It is true I had no knowledge of whether Pasel actually filed a disclaimer. When I used the words "entered a disclaimer" I meant entered a disclaimer in his specification. Perhaps I should have described this as a "quasi disclaimer." I will refer to the Pasel patent so that my meaning is clear. Lines 19–21 read as follows:

> "It should also be pointed out that alloys of iron which contain chromium only as the addition have already been proposed for the manufacture of articles which must be capable of resisting the action of acids."

It seems to me that Pasel disclaimed any endeavor to patent this particular type of alloy. Lines 22 to the end of the paragraph read:

> "Iron-nickel-chromium alloys were also already known, which contained 16 to 38 per cent iron, 5 to 60 per cent nickel, and 24 to 57 per cent chromium, in which therefore the sum of the chromium and nickel contents amount to 62 per cent at the least and 84 per cent at the most. From these known alloys which were principally used as additions in the manufacture of steel, those employed according to the present invention differ by the fact that in them the sum of the chromium and nickel contents can only lie between 19 and 60 per cent. But I do not claim such alloys *per se* but only articles (such as vessels, tubes, parts of machinery, etc.) which require a high power of resistance to attack by acids and great strength, made from such alloys. That iron-chromium-nickel alloys possess the property of resisting acids to a particular degree has not been known heretofore and articles of the kind mentioned have never been made from such alloys."

I note that the Pasel limit, according to this statement, is 60 per cent of nickel and chromium, but alloys of 62 per cent nickel and chromium were well known according to Pasel in his specification. It is true that Pasel says that these high percentages of alloys were only used previously as additions in the manufacture of steel. Is it not fair to say that 62 per cent of alloy is rather high for just a plain ordinary addition, the purpose of which was merely the general use of alloys? Surely, 62 per cent of alloy must have been there for a very specific purpose and not a mere addition.

Furthermore, is it not reasonable to suppose that an alloy containing 60 per cent of nickel and chromium taken together would have just as many acid-resisting characteristics if it had 62 per cent?

Mr. Armstrong.

Therefore, 62 per cent and higher nickel and chromium together must have had the same acid-resisting characteristics as those containing between 19 and 60 per cent. The fact that Pasel says that these alloys between 62 and 84 per cent nickel and chromium content in iron were well known and that he does not claim these alloys *per se*, and only some specific use of them, shows that he had to disclaim the desire to claim these alloys *per se*. Therefore, in my understanding of the term in the ordinary sense and not a legal sense, he automatically entered, perhaps again, a quasi disclaimer.

My paper was largely a review of the patents adhering to the facts as related with some explanation of just what they meant to me at least. I trust that with this explanation Mr. Benno Strauss will not feel that I have unfairly explained, or made statements, concerning the Pasel patent of 1913.

Referring to the last remark of Mr. Benno Strauss in which he says that chromium nickel compositions are far superior by reason of their strength properties, I heartily agree with this statement as nickel additions to chromium from an acid-resisting point of view, do not, so far as I have been able to see, affect the situation very markedly, but nickel additions to chromium do affect the physical properties of the alloy, and additions of other alloys such as silicon to nickel and chromium result in a still further improvement.

Mr. Fahrenwald.

MR. F. A. FAHRENWALD.[1]—In reply to Mr. French, my views on the high-temperature properties of available alloys as indicated in my paper are based on more than ten years of rather close association with the development and commercial production of special alloys and in the design and use of equipment made therefrom, and it is from sad experience rather than choice that I recognize the relatively low maximum values available in alloys.

In connection with predictions concerning possibilities for future development it must be recognized that cost, production, fabrication and other factors outside of mere physical strength or chemical resistivity cannot be overlooked. Alloys can be made now which are resistant to oxidation at 3100° F. and of considerable physical strength at that temperature, but they cost several dollars per pound, cannot be machined, can hardly be cast in even simple shapes and are quite brittle cold.

The question of modification of existing alloys is extremely complicated unless this be limited in each case to a consideration of a single property for a rather narrow temperature range. Within certain temperature limits, for example, the physical strength of iron-

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[1] Consulting Engineer, Cleveland, Ohio.

Mr. Fahrenwald. chromium alloys may be greatly increased by adding carbon, while outside of these limits the high-carbon alloy may be of considerably lower strength; that is, the temperature - physical strength curves would cross several times in going from room temperature to the melting point. It is not difficult to secure some one property in an extremely high degree, but most requirements call for well balanced alloys in which a number of properties must be given consideration.

When carbon is added to chromium-iron alloys, strength and hardness are increased up to certain percentages, but practically all of the carbon above the solid-solution saturation point is present as chromium carbide or a double carbide of chromium and iron so that an increase in carbon content results in a decrease in the percentage of chromium present as a solid solution in iron. I have found that resistance to corrosion or oxidation is to a large extent proportional to the chromium content in this solid solution. This will illustrate that it is often necessary to go in opposite directions to meet different requirements in the same alloy.

As to reproducibility in these alloys, I can state from my own experience that castings or ingots can be produced with chemical composition and physical properties as close to a given standard as for ordinary steel.

Replying to Mr. Knerr, crystallin and constitutional or phase stability throughout the temperature ranges encountered in service are essential requirements in heat-resisting alloys for successful continuous performance. Any recrystallization or grain growth or any precipitation or resolution of any constituent when subjected to operating temperature conditions will render the alloy unfit for high temperature equipment. The necessity for the practical elimination of all possibility of such internal changes has had considerable influence in determining standardized compositions of the heat-resisting alloys described in this paper. This type of stability is obtainable to a high degree in alloy castings and I have specimens of such alloys which after more than 10,000 hours' service at 1800° F. show practically the same structure as the control bar from the same heat.

Considerable difficulty is encountered from this source, however, in most of the rolled, forged, or otherwise wrought forms of similar alloys due, largely, to normal recrystallization but to some extent also to transformation points. For example, a tough rolled bar of an iron alloy with about 18 per cent chromium, 2 per cent silicon, 0.40 per cent carbon will become quite crystallin and brittle (when cold) if held at 1800° F. for a short time only. The 25-per-cent chromium-iron alloys also have a tendency to become brittle when alternately heated and cooled.

Mr. Fahrenwald.

Closure by letter.—In my brief and very general consideration of an extremely broad subject I intentionally avoided any argumentative discussion of any one of its many divisions and it would seem that differences of opinion in connection with certain details are based more upon different points of view than upon any fundamentally different beliefs.

Mr. Lessells, in his discussion of my paper, states that "it is only by a combination of experiment and analysis that a true picture can ultimately be found." To these two, I would add another factor, "application under industrial conditions," because experiment and analysis in the ordinary sense will not show the industrial value of a material in use under conditions where the time factor predominates.

The very positive opinions expressed by Mr. Lessells regarding elastic properties do not include a proper consideration of the time factor and if there can be presented any data concerning the modulus of elasticity or proportional limit of any alloy when subjected to stress continuously, for a period of say a year, at temperatures above 1000° F. such information will be exceedingly valuable.

As to the serviceability of heat-treated steels, it is quite certain that the time of drawing back would have to be extended considerably beyond ordinary practice in order to make that particular steel stable for continuous service at temperatures only a little below that of drawing.

It is my belief at the present time that, as a matter of fact, the properties known as the modulus of elasticity and proportional limit exist in kind just as truly near the melting point as at atmospheric temperatures (which *is* near the melting point for such metals as lead and tin) the difference being one of degree only: dependent upon both time and temperature of the test.

The value of mathematical analysis in the solution of thermal problems cannot be disputed and I regret that anything in this paper waves aside the mathematician because when out of sight of the piercing eye of the practical industrialist it must be confessed that I employ every tool of mathematics that comes within the scope of my limited ability in this direction.

Messrs. Anderson and Enos.

MESSRS. ROBERT J. ANDERSON[1] and GEORGE M. ENOS[2] (*Authors' closure by letter*).—Regarding the discussion by Mr. Waddington, the authors do not agree that high-chromium steels do not stand up under mine-water service conditions. It may very well be that certain compositions in these steels do not withstand service corrosion

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[1] Formerly Metallurgist, U. S. Bureau of Mines, Experiment Station, Pittsburgh, Pa.

[2] Instructor in Metallurgy, University of Cincinnati, Ohio.

Messrs. Anderson and Enos. as well as others, but the whole class cannot be condemned as unsuitable. It is quite well known by mine operators that certain high-chromium alloys (really varieties of stainless steel) are exceptionally resistant to the action of acid mine waters, not only in accelerated tests but also in simple immersion tests, and these same alloys have been tested in the form of pump parts and found to be quite satisfactory.

Turning now to the remarks of Mr. Hall, the bulletin referred to gives the results obtained in experiments at the Pittsburgh Station of the U. S. Bureau of Mines during 1923–24, in continuation of the corrosion work previously reported in *Bulletins Nos. 4, 5,* and *6* (Coal Mining Investigations of the Carnegie Institute of Technology). Mr. Hall states that for metals below hydrogen in the electromotive series, the acidity of the corroding solution within the limits met in mine waters has little effect, but the concentration of ferric ion is the controlling factor in corrosion rates. The authors would like to suggest that, in considering results obtained from a study of substantially pure metals, in relation to the electromotive force series of the metals, it must be remembered that care should be taken in interpreting such results as applicable to alloys. In alloys, and particularly complex alloys, the position with reference to the electromotive force series is not necessarily known from the composition. Since ferric ion is present in natural mine waters, and Mr. Hall states that it functions for metals both above and below hydrogen in the electromotive force series, the authors would suggest that variation of acidity is not necessary; or, rather, why should the effect of ferric ion be omitted when varying the acidity? Ferric ion concentration certainly has marked effect on corrosion rates in some instances. At the same time, polarizing effects and resistance to oxidation because of the formation of films and coatings may bring about conditions where the *potential* oxygen present means little.

Several factors must be considered when the simpler rotation test is suggested in place of the accelerated electrolytic or long-time immersion tests. For metals and alloys known to corrode uniformly the imposed electric current can apparently be dispensed with. For alloys whose corrosion characteristics are unknown, it seems more advisable to the authors to impose a small current, since even if the current will not change the corrosion rate over that obtained in the rotation test (as stated by Mr. Hall), it will yield the normal pitting effects of the alloy (if the alloy does pit) and its typical corrosion characteristics can be secured in a short time.

Mr. McAdam.

MR. D. J. MCADAM[1] (*Author's closure, by letter*).—In the second paragraph of Mr. Lessells' discussion he apparently implies that the endurance limit in bending always becomes higher than the proportional limit in tension. This is not true, however, of the majority of carbon and alloy steels used in machinery.

Mr. Lessells points out that it appears to be true for all steels, as well as for corrosion-resistant steels, that the ratio of endurance limit to ultimate strength is higher in the heat-treated than in the annealed condition. This comment, however, is not new since the subject was discussed by the author in this paper and in a previous one.[2]

Mr. Lessells seems to be surprised that facts have been presented without discussion of the underlying causes. And yet with the facts before him Mr. Lessells' discussion has not contributed much toward the theory of this subject.

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[1] Metallurgist, U. S. Naval Engineering Experiment Station, Annapolis, Md.

[2] D. J. McAdam, Jr., "Endurance Properties of Steel: Their Relation to Other Physical Properties and to Chemical Composition," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 56 (1923).

ACCELERATED FATIGUE TESTS AND SOME ENDURANCE PROPERTIES OF METALS[1]

BY D. J. MCADAM, JR.[2]

DEVELOPMENT OF THE ACCELERATED FATIGUE METHOD

In an actual fatigue test of a rotating cantilever or rotating beam specimen the load is usually allowed to remain constant throughout the test. The bending moment, and hence the nominal stress, remains constant. In an alternating-torsion test with a machine of the spring type developed at the Naval Engineering Experiment Station (**1**, **2**),[3] the torsional moment throughout the test remains practically constant. Although as the specimen weakens by fatigue the stress tends to decrease, this decrease is usually so slight that it can be neglected. In tests in which the specimen is stressed beyond its elastic limit, an auxiliary spring (**2**) can be used to hold the stress practically constant. Until recently alternating-torsion tests at the Naval Experiment Station with the machine of the inertia type (**3**), (**4**) have also been made under such conditions that the torsional moment throughout the test could be considered practically constant. All these methods of determining the endurance properties of metals by test to failure under constant nominal stress range may be called "fatigue methods" to distinguish them from the "accelerated fatigue method" to be described.

In an alternating-torsion test with a machine of the inertia type the torsional moment tends to increase as the specimen fails. This is due to the fact that the amplitude of oscillation of the flywheel depends not only on the radius of crank-pin motion but also on the twist of the specimen. As a specimen fails, the twist tends to increase. The automatically increased twist means automatically increased amplitude of oscillation of the flywheel and hence automatically increased torque and nominal stress. With the short F type specimen used in previously described tests (**4**) and illustrated in Fig. 1 this automatic increase of stress is so slight that it has been neglected.

The fact that the nominal stress, in an alternating-torsion test with a machine of the inertia type, tends to increase during fatigue failure suggested the idea that, instead of striving for constant stress throughout a test, it might be better to so adjust conditions as to secure the greatest practicable automatic increase of stress. It is evident that to obtain the greatest practicable automatic increase of stress the ratio of the amplitude of oscillation of the flywheel due to the twist of the specimen to the total amplitude of oscillation must be made as great as is practicable. For this purpose the ratio of length to diameter of specimen should evidently be made as great as is practicable and the radius of crank-pin motion should be made as small as is practicable and consistent with the range of torsional stress desired. Investigation of the endurance properties of metals under such conditions has resulted in the development of a method of endurance testing that may be called an "accelerated fatigue method."

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[1] Published by permission of the Secretary of the Navy.

[2] Metallurgist, U. S. Naval Engineering Experiment Station, Annapolis, Md.

[3] The boldface numbers in parentheses refer to the papers given in the list of references appended hereto.

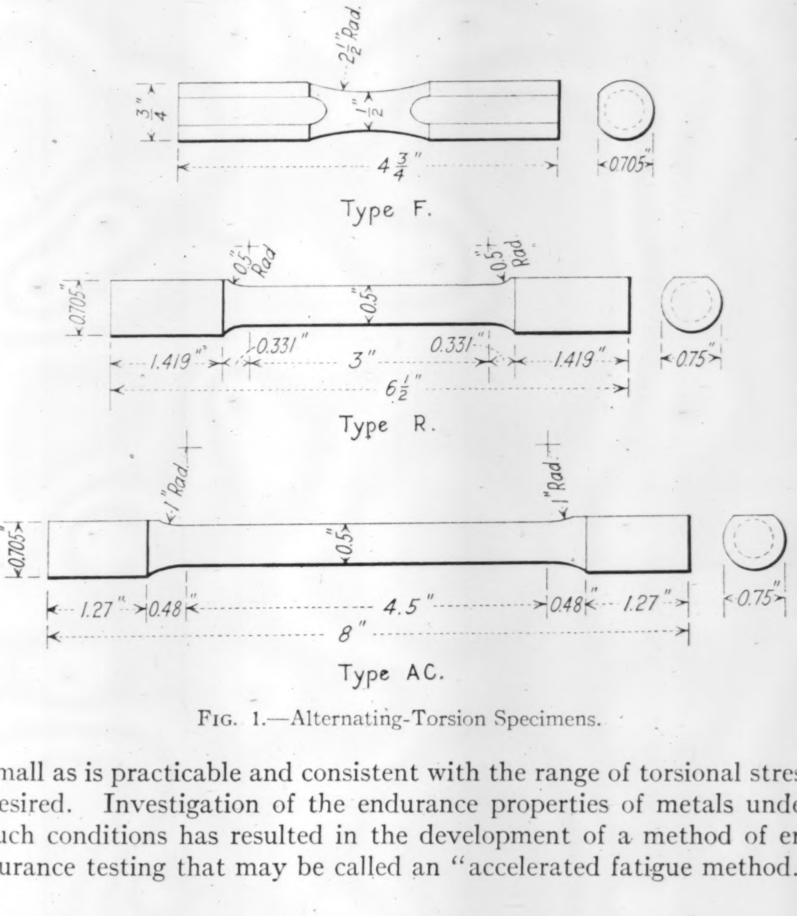

Fig. 1.—Alternating-Torsion Specimens.

The Deflection Method and its Relationship to the Accelerated Fatigue Method

In addition to the "fatigue method" and "accelerated fatigue method" there is a third method which is of limited application in determining the alternating-torsion endurance properties of metals, a deflection method. This method was described by Gough (5). In obtaining endurance limits by the deflection method, stress-deflection graphs are plotted and an attempt is made to determine the stress above which the graph ceases to be a straight line. Above this point, which can be determined with varying accuracy, increase of deflection is no longer proportional to increase of stress. The determination of this point is analagous to the determination of the proportional limit in a tension test and is surrounded with the same difficulties.

In an alternating-torsion test with the inertia machine, the angle of twist of the specimen is readily determined by subtracting the amplitude of oscillation of the flywheel due to crank-pin motion from the total amplitude of oscillation. These values may be readily measured by means of the optical lever system used in this machine. Stress-deflection graphs may, therefore, be obtained by gradually increasing the speed of the machine and taking readings at regular intervals.

Table I.—Chemical Composition.

All values are expressed in per cent.

Material	Designation	C	Mn	P	S	Si	Cu	Zn	Sn	Al	Ni	Cr	Fe	Pb	Mg
Chrome-Nickel Steel	AO	0.368	0.681	0.012	0.013	0.13	....	....	....	....	1.36	0.65	....	....	....
Duralumin	BI	....	0.593	....	....	....	3.81	....	....	93.39[b]	....	....	0.659	....	....
“Inco” Nickel, hot rolled	AW	....	0.184	....	0.025	0.008	0.159	....	....	....	....	....	0.59	....	....
Monel metal, hot rolled	AA[a]	0.18	1.44	0.017	0.039	0.02	29.54	....	....	....	....	....	2.13	....	....
Copper, Electrolytic, cold rolled	BO	....	....	....	....	....	....	....	....	....	....	....	0.0052	Less than 0.002	....

[a] Manufacturer's results.
[b] By difference.

In the absence of experimental data there would be no reason to assume that in a specimen subjected to alternating torsion the limit of proportionality of deflection to stress corresponds to an endurance limit. Gough (5), however, determined experimentally that in some steels the limit of proportionality corresponds rather closely to the "endurance limit." Investigation of the method at the Naval Experiment Station has shown that it is not generally applicable to nonferrous metals and does not give accurate results with all kinds of steel (6).

It should be pointed out that the accelerated fatigue method does not depend, as does the deflection method, on determination of a limit of proportionality of deflection to stress. The accelerated fatigue method consists in determination of the stress above which the deflection, and hence the stress, increases automatically until the specimen breaks.

SCOPE OF INVESTIGATION OF ACCELERATED FATIGUE METHOD

To investigate the possibilities of the accelerated fatigue method, tests were first made on steels. Dimensions of specimen, radius of crank-pin motion, inertia of flywheel, and frequency of oscillation were varied so as to obtain widely different ratios of total amplitude of oscillation to the amplitude of oscillation due to crank-pin motion.

TABLE II.—AVERAGE RESULTS OF STATIC TENSION TESTS.

Each value is the average of two specimens, except as indicated.

Material	Designation	Cooled in	Drawn at —deg. Fahr.	Tensile Strength, lb. per sq. in.	Johnson's Limit, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elastic Limit, lb. per sq. in.[a]	Proof Stress, lb. per sq. in.[a]	Elongation in 2 in., per cent	Reduction of Area, per cent
Chrome-Nickel Steel	AO	Water	1000	140 400[b]	125 500[b]	119 500[b]	119 500	126 000	21.0[b]	62.9[b]
Duralumin, hot rolled	BI	As received		52 300	24 100	18 600	20 000	25 000	21.7	33.5
"Inco" Nickel, hot rolled	AW-1	As received		60 200[c]	21 700[c]	18 700[c]	18 700	24 000	52.3[c]	74.7[c]
Monel Metal, hot rolled	AA	As received		89 800[c]	55 300[c]	44 000[c]	55 000	60 000	36.5[c]	69.5[c]
Copper, cold rolled	BO	As received		40 400	[d]	[d]	8 000	13 000	24.5	66.0

[a] One determination only.
[b] Average of four determinations.
[c] Average of three determinations.
[d] Stress-strain graphs curved from origin.

TABLE III.—RESULTS OF STATIC TORSION TEST

Individual results, except as noted.

Material	Designation	Cooled in	Drawn at —deg. Fahr.	Nominal Torsional Strength, lb. per sq. in.	Johnson's Limit, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Angle of Twist per linear inch, at proportional limit, min.	Angle of Twist per linear inch, at break, deg.
Chrome-Nickel Steel	AO	Water	1000	92 400	79 400	71 000	93	277
Duralumin, hot rolled	BI	As received		33 400	21 400	16 600	40	81
"Inco" Nickel, hot rolled[a]	AW-1	As received		71 100	23 200	19 500	13.5	819
Monel Metal, hot rolled[a]	AA	As received		69 000	31 900	27 700	24	746
Copper, cold rolled	BO	As received		34 000	[b]	[b]	[b]	795

[a] Average of two determinations.
[b] Stress-strain graph curved from origin.

The investigation was then extended to non-ferrous metals. The results obtained have been summarized by stress-cycle graphs showing both automatic and artificial changes of stress during the progress of each test. The results of some of these accelerated fatigue tests have also been summarized by stress-strain graphs for comparison with results obtained by the "deflection method." For comparison with results obtained by the "fatigue method" some of the results of accelerated fatigue tests have also been plotted on a semi-logarithmic scale.

MATERIAL

The material was in the form of cylindrical bars about 1 in. in diameter. The International Nickel Co., the American Brass Co., and the Aluminum Co. of America generously cooperated in this work by furnishing some of the material. The chemical composition and mark used to designate each kind of material are listed in Table I.

Heat Treatment.—The chrome-nickel steel used in this investigation was heated to 1550° F., held at this temperature for 1 hour, quenched in water, reheated to 1000° F., held at this temperature for 2 hours, and cooled in the furnace. The non-ferrous metals were tested as received.

TENSION AND TORSION TESTS

Results of tension and torsion tests are given in Tables II and III. The elastic limit values in Table II are the stresses above which "permanent set" begins. By "proof stress" is meant the stress that produces a permanent set of 0.0002 in. in a gage length of 2 in. Proof stresses were obtained from graphs in which abscissas represent permanent set.

DETAILS OF ACCELERATED FATIGUE METHOD

Fatigue Acceleration Index or Sensitivity Ratio.—When the ratio of the amplitude of oscillation of the flywheel due to twist of the specimen to the total amplitude of oscillation is large, even a slight automatic increase of twist during an endurance test results in important increase of stress. This automatic increase of stress causes the specimen to fail after fewer cycles than if the nominal stress remained constant. In other words, fatigue of the specimen is automatically accelerated. The degree of this fatigue acceleration depends on the ratio of amplitude of twist to total amplitude of oscillation. Evidently, therefore, this ratio is an important index of the degree of fatigue acceleration. For an endurance test by the "fatigue method" this ratio would be zero, thus indicating that there is no fatigue acceleration. The maximum value for this ratio would be 1. This maximum would be attained if it were possible for the entire amplitude of oscillation to be twist amplitude. Under such conditions the maximum fatigue acceleration would be secured.

A more convenient fatigue acceleration index, however, is the ratio of total amplitude of oscillation of the flywheel to amplitude of oscillation due to disk-crank radius. This index, which was adopted for use, has a wider numerical range than the index previously discussed. For a test by the "fatigue method" this index is 1. If it were possible for the entire amplitude of oscillation to be twist amplitude, the fatigue acceleration index would be infinity.

The fatigue acceleration index has also been found to be a good index of the sensitivity of any combination of specimen, flywheel inertia, and disk-crank radius to change of frequency of oscillation of flywheel. With a short specimen, for which the acceleration index approaches 1, the stress varies approximately as the square of the frequency. With increase in the fatigue acceleration index, the stress varies more than in proportion to the square of the frequency. It has been found that the stress varies approximately as S^{2F}, where S represents frequency and F represents the fatigue acceleration index. If it were possible for the entire amplitude of oscillation of flywheel to be twist amplitude, the sensitivity of the apparatus to change of frequency or to any slight change in the specimen would be infinite. With a high fatigue acceleration index, therefore, the apparatus becomes so sensitive that it is too unstable for practical purposes. It has been found that a fatigue acceleration index of about 4 is most suitable for fatigue acceleration tests. Fairly good results, however, are obtained when the index is as low as 2.5. Since the fatigue acceleration index is a measure of the sensitivy of the apparatus to change of frequency as well as to changes in the specimen during an endurance test, it has also been called the "sensitivity ratio."

Since with a sensitivity ratio of 4 the stress sometimes varies as nearly the eighth power of the speed of the motor it might be thought at first that this sensitivity would be too great for use in a practical endurance test. Such a conclusion, however, is not correct. The speed of the inertia machine is regulated within 0.5 per cent of the desired value. An operator, however, is constantly at hand to keep the speed within even narrower limits. It is very seldom that under these conditions the speed varies as much as 0.5 per cent above or below the desired value. The effect of such slight occasional variations on the endurance of metals, especially of non-ferrous metals, is negligible. It is safe to assume that the effective average speed can be kept within 0.1 per cent of the desired value. With a sensitivity ratio of 4, the effective average stress, therefore, is probably within 0.5 per cent of the desired amount.

Machine and Specimen Constants.—As described in a previous paper the oscillation range of the flywheel is measured by the motion of a beam of light reflected to a scale from a mirror attached to the flywheel. The apparatus is so arranged that the total scale range of the beam of light in centimeters is a multiple of the number of degrees of oscillation range of the flywheel. This total scale range of the beam of light is made up of a scale range due to disk-crank motion and a scale range due to twist of the specimen. The scale range due to disk-crank motion, which may be called "crank scale range," is a constant multiple of the disk-crank radius. The scale range due to twist, which may be called the "twist scale range," depends on the dimensions of the specimen and the modulus of rigidity of the material.

The inertia of the flywheel may be adjusted to many different values by means of added rings. For convenience in calculation it has been found necessary to prepare a table of machine constants which gives the stress per centimeter of total scale range for each value of flywheel inertia and for a wide range of speeds at intervals of 25 r.p.m. From any total scale range and the appropriate machine constant the stress in the specimen may readily be calculated.

The twist scale range depends on the dimensions of the specimen, the modulus of rigidity of the material, and the stress. For convenience in calculation, a table has been prepared which gives the twist scale range per thousand pounds stress for each type of specimen and kind of material. By means of this table of specimen constants the twist scale range for any stress may be readily calculated.

To test a specimen at any desired stress and sensitivity ratio the necessary twist scale range is calculated, using the table of specimen constants. The crank scale range is then obtained by dividing the twist scale range by the desired sensitivity ratio less one. The total scale range is the sum of the twist scale range and the crank scale range. The desired stress divided by the total scale range in centimeters gives the machine constant that must be used. Since this machine constant can be obtained with several combinations of flywheel inertia and frequency, the combination that gives the desired frequency is selected from the table of machine constants. The frequency usually selected is as near as possible to the maximum speed obtainable with the machine, 2150 r.p.m.

Measurement of Frequency of Oscillation.—For instantaneous measurement of the frequency of oscillation of the flywheel, which is equal to the speed of the machine in revolutions per minute, a vibrating reed tachometer is used. The average speed is also determined by readings of a revolution counter taken at five-minute intervals.

Critical Frequencies of Oscillation.—When the actual frequency of oscillation coincides with the natural frequency of oscillation of any combination of type of specimen and flywheel inertia, there is a sudden large increase in the amplitude of oscillation. This increased amplitude of oscillation occurs within a narrow range of speed. A change of speed of only 10 r.p.m. will carry the apparatus into and beyond the critical speed. For every value of flywheel inertia, every type of specimen, and every kind of material, therefore, it has been found necessary to investigate the entire range of speed to be used and to determine the critical frequencies. With some combinations, two different critical frequencies are encountered within the speed range to be used. A table of these critical frequencies has been prepared.

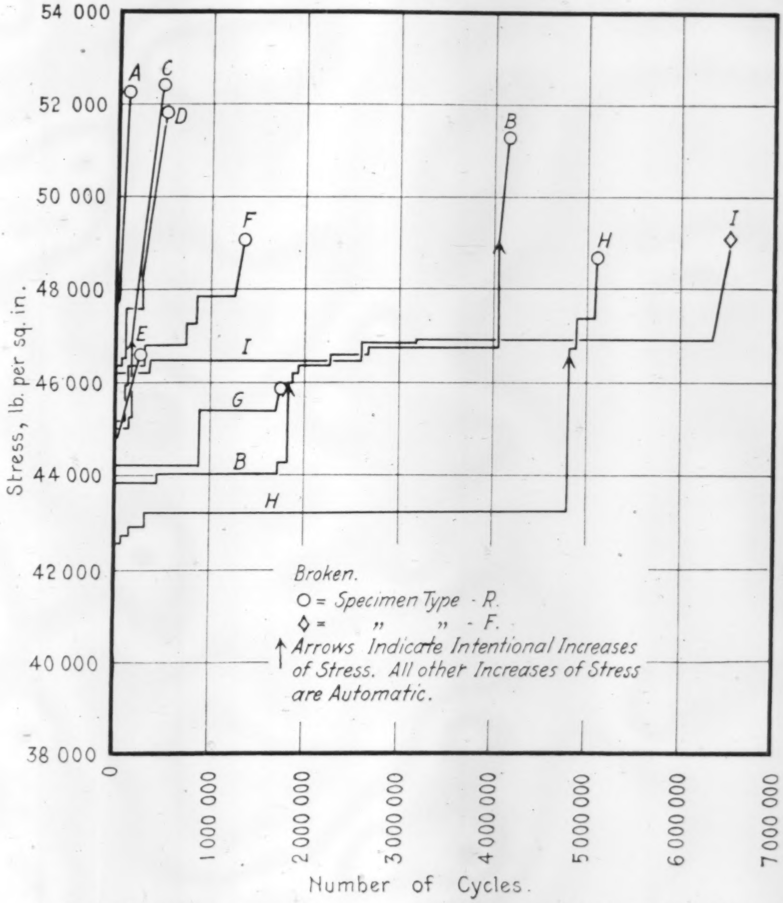

Fig. 2.—Results of Alternating-Torsion Tests, Material AO, Chrome-Nickel Steel: Carbon, 0.37; Nickel, 1.36; Chromium, 0.65 per cent.

In all investigations with an alternating-torsion machine of the inertia type it is important that such a table of critical frequencies be used. If critical frequencies be not avoided, misleading results will be obtained and incorrect conclusions will be drawn. In Gough's investigation of the deflection method(5), for example, he apparently encountered two critical speeds in making speed-deflection experiments with a nickel specimen. His Fig. 8 is a good illustration of the effect of critical frequencies on a deflection graph. Gough incorrectly attributes the abrupt peaks in his graphs to yield and recovery of the nickel.

RESULTS OF ENDURANCE TESTS

Results Obtained with Steel.—First experiments by the accelerated fatigue method were made with chrome-nickel steel, material AO. The results are shown graphically in Fig. 2. In this figure, each graph represents the stress-cycle conditions throughout an endurance test of a specimen. Each graph is designated by a letter. Vertical lines terminated by arrows indicate increases of stress due to intentional increases of disk-crank radius or of speed. All increases of stress not indicated by arrows were automatic.

As shown by graphs *A* and *B*, when the stress was 48,000 lb. per sq. in. or more, it increased automatically and rapidly until the specimens failed after only about 100,000 cycles. The test of specimen B was started at 44,000 lb. per sq. in. After the test had continued for nearly 2,000,000 cycles with practically no automatic increase, the stress was raised to 46,000 lb. Automatic increase of stress at once began and continued with decreasing rapidity for about 2,000,000 cycles. When the stress was then raised to 49,000 lb. per sq. in. the above-mentioned rapid increase of stress began and the specimen soon failed.

Test of specimen C was started at 45,000 lb. per sq. in., but the stress was soon afterward raised to about 47,000 lb. Immediate automatic increase of stress began and the specimen failed after about 300,000 cycles.

Specimen D, which was started at a stress of 46,300 lb., failed after about 400,000 cycles. Specimens E and F, which were started at a stress of about 45,000 lb., showed rapid automatic increase of stress; specimen E failed after 300,000 cycles, whereas specimen F endured 1,400,000 cycles. Test of specimen G was begun at a stress of 44,000 lb. This specimen endured nearly 2,000,000 cycles with automatic increase of stress.

Specimen H was started at a stress of 42,500 lb. The stress increased rapidly to 43,200 lb. and then remained constant until, after nearly 5,000,000 cycles, the stress was raised to 46,500 lb. Rapid automatic increase then began and the specimen soon failed.

These experiments seem to indicate that, as obtained by the "accelerated fatigue" method, the endurance limit for this material is about 43,000 lb. per sq. in. For comparison with results obtained by the "fatigue method," however, it seemed desirable to test a short specimen such as the one used in previously described (4) alternating-torsion tests. Accordingly, specimen I was tested at an initial stress of 46,200 lb. Even with this short specimen, there was some automatic increase of stress during the endurance test. The specimen endured 6,500,000 cycles, however, before failing. Evidently, therefore, the "endurance limit," as determined by the "fatigue method," is about 45,000 lb. per sq. in.

By disregarding all automatic increases of stress, and plotting only initial stresses and artificial increases, a simplified representation may be made of the results shown in Fig. 2. This method of plotting results of endurance tests is illustrated in Fig. 3.

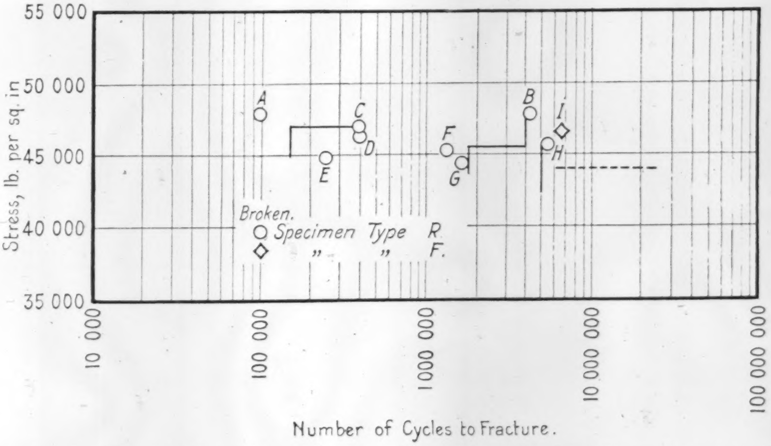

FIG. 3.—Results of Alternating-Torsion Tests, Material AO, Chrome-Nickel Steel.

In this figure, each specimen is designated by the same letter by which it is designated in Fig. 2. Specimen F, for example, as shown in Fig. 2, was subjected to considerable automatic increase of stress during the test. To represent the same specimen in Fig. 3, the point marked F is plotted at the initial stress and at the total number of cycles endured.

As indicated by Fig. 3 the endurance limit is apparently about 44,000 lb. This is slightly lower than the value obtained by the fatigue method as represented by the short specimen I.

The possibility of determining the endurance limit of this steel by the "deflection method" was also investigated. For this purpose, stresses were plotted as ordinates and angles of twist as abscissas. Some results obtained by this method are shown in Fig. 4. Specimens J and K were tested by the deflection method. The stress was increased gradually and strain readings were taken at frequent intervals. At each of the points indicated by arrow tips in graphs *J* and *K* the stress was held constant only long enough to allow the strain readings to be taken. Graph *J*, although it extends to a stress above 50,000 lb. per sq. in., is apparently straight. Below a stress of about 40,000 lb., graph *K* is practically straight. Above this point curvature begins and increases gradually and slowly. From this graph it would be difficult to estimate the endurance limit within 5000 lb. per sq. in. The difference in curvature between graphs *J* and *K* is probably due to the greater sensitivity ratio used in the test of specimen K.

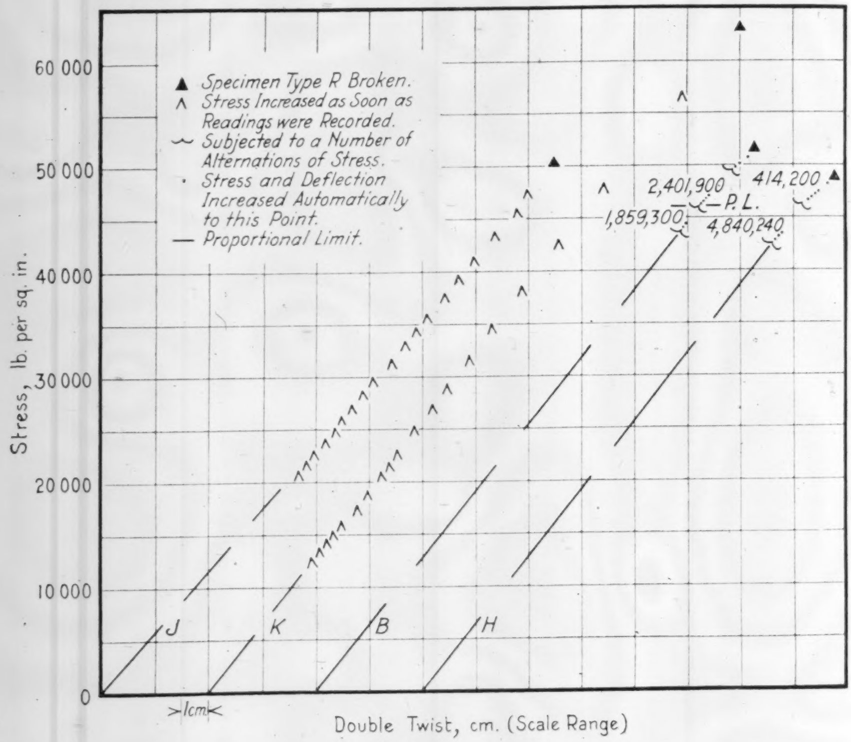

FIG. 4.—Results of Alternating-Torsion Tests, Material AO, Chrome-Nickel Steel: Carbon, 0.37; Nickel, 1.36; Chromium, 0.65 per cent.

For comparison of the deflection method with the accelerated fatigue method, tests of specimens by the accelerated fatigue method

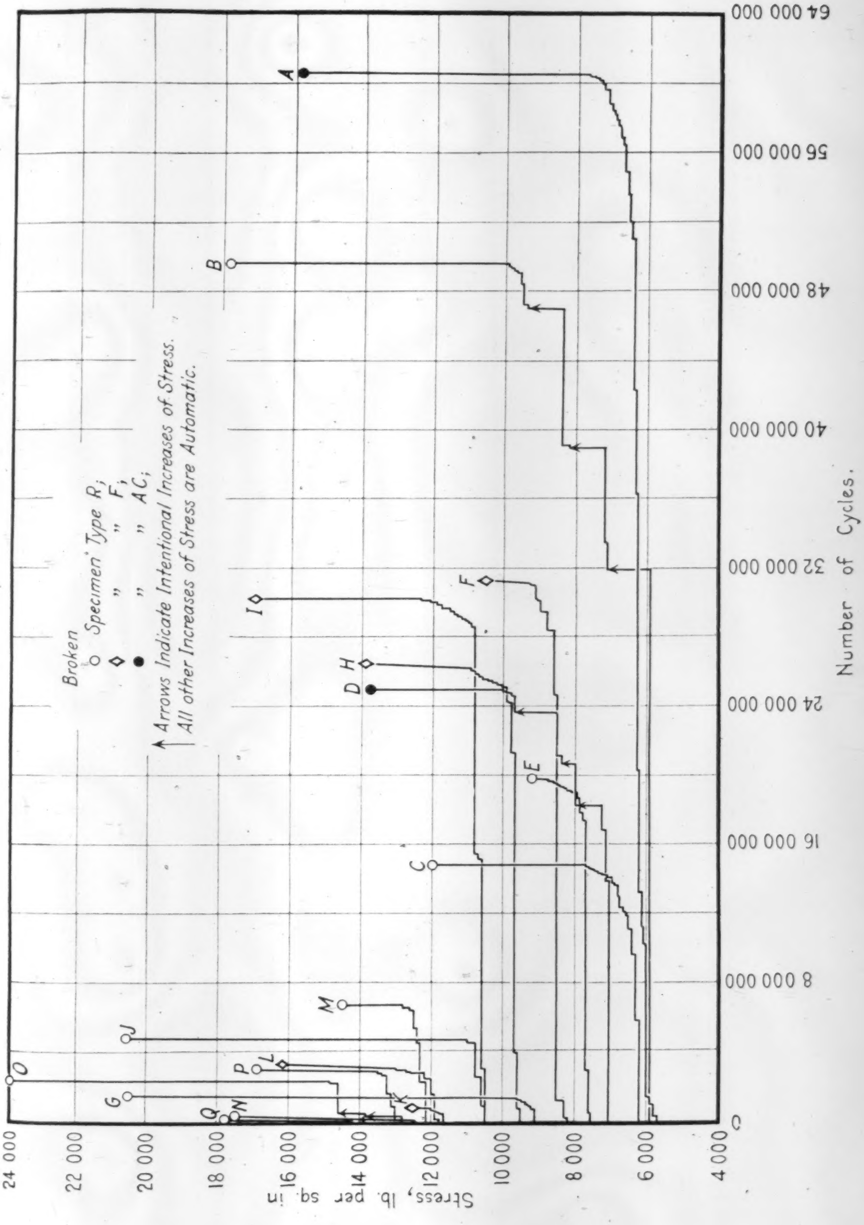

FIG. 5.—Results of Alternating-Torsion Tests, Material BI, Duralumin.

are represented also by stress-strain graphs. Graphs *B* and *H* of Fig. 4 represent the same specimens that are represented in Fig. 2 by stress-cycle graphs and are designated by the same letters. As shown in Fig. 4, graphs *B* and *H* have definite change of direction at points where automatic increase of stress begins. These "proportional limits" are designated "P.L." These results seem to indicate, therefore, that with heat-treated alloy steels the accelerated fatigue method gives more accurate results than the "deflection method."

Results Obtained with Duralumin.—A test of duralumin by the deflection method, as illustrated by graph *N* of Fig. 7, showed that the limit of proportionality of the stress-deflection graph is about 14,000 lb. per sq. in. The first tests of duralumin by the accelerated fatigue method were, therefore, made at about this stress. As shown in Fig. 5, these specimens failed very quickly. Other specimens were then tested at successively lower initial stresses until an initial stress of about 6000 lb. per sq. in. was reached. Specimens tested at an initial stress of less than 6000 lb. per sq. in. endured many million cycles and failed only after large artificial or automatic increases of stress.

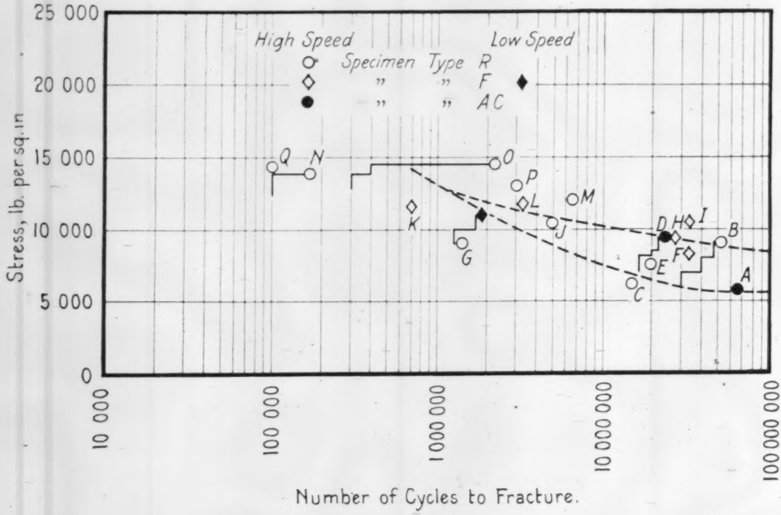

FIG. 6.—Results of Alternating-Torsion Tests, Material BI, Duralumin.

It will be noticed that as the initial stress is lowered, the inclination of the first part of the graph decreases. When the initial stress is below a critical value of about 6000 to 7000 lb. per sq. in, the first part of the graph is sometimes horizontal for many million cycles. In a graph with higher initial stress, the automatic increase of stress, which is at first rapid, decreases in rapidity until the graph is horizontal. After remaining horizontal for a distance that decreases with increase in the initial stress, the stress begins to increase again and the inclination of the graph becomes gradually greater until the specimen fails. The typical accelerated fatigue graph, therefore, is at first convex upward, then horizontal, and then concave upward.

It seems evident that with automatically increasing stress, specimens would fail after much fewer cycles than under nominally constant stress. It seems probable that specimens A and B illustrated in Fig. 4, if the nominal initial stress had been held constant throughout the test, would have endured several hundred million cycles before failure.

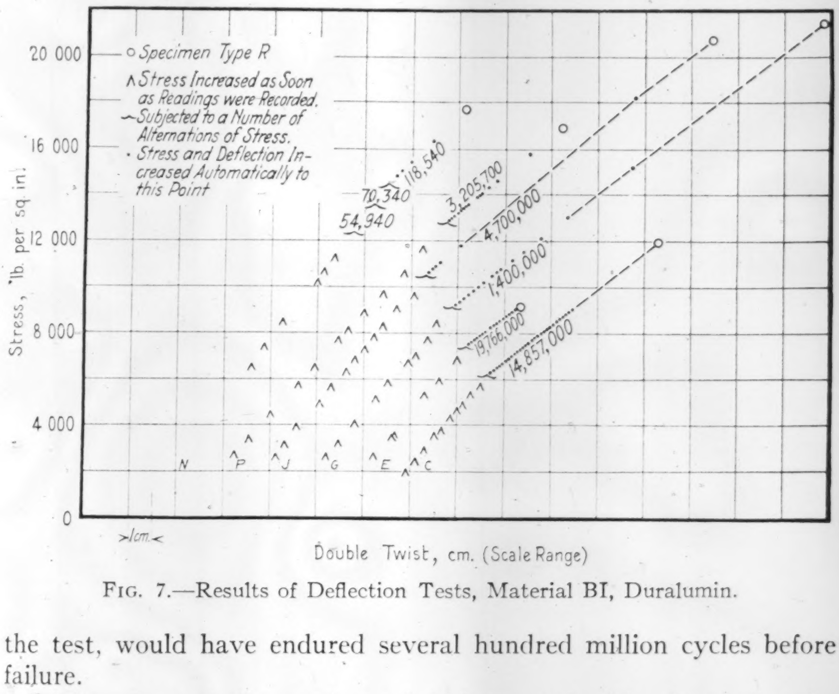

Fig. 7.—Results of Deflection Tests, Material BI, Duralumin.

The effect of the accelerated fatigue method in shortening the time of an endurance test cannot be quantitatively estimated at present. For such a quantitative estimate, a comparison of graphs obtained by this method with graphs obtained by the fatigue method would be necessary. Such a comparison cannot now be made. To obtain some idea, however, of the probable difference in number of cycles between an accelerated fatigue test and a fatigue test, several endurance tests were made with a short specimen, type F. The results are recorded in Figs. 5 and 6. As shown by the broken line in Fig. 6 the composite graph representing results obtained with the

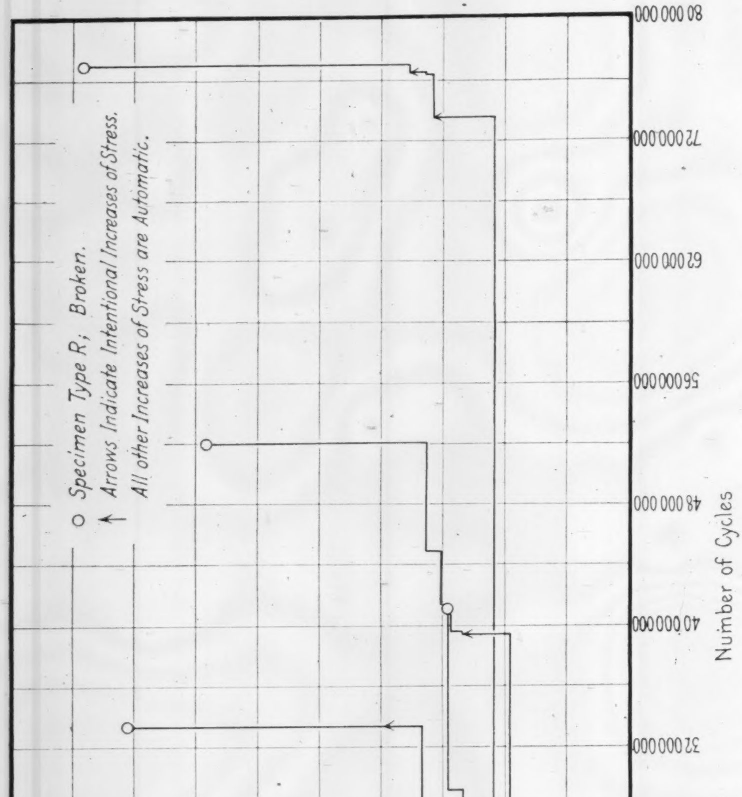

FIG. 8.—Results of Alternating-Torsion Tests, Material AW-1, Hot-Rolled Nickel.

short specimens slopes downward less rapidly at first than does the composite graph representing results obtained with the long specimens. And yet, even with the short specimens as shown in Fig. 5, there is considerable fatigue acceleration. One would expect, therefore, that the slope of a composite "accelerated fatigue" graph would be greater at first than that of a composite "fatigue" graph, and that an approximate endurance limit would be reached sooner and would be more clearly defined in the former graph than in the latter. The more nearly horizontal the composite "fatigue" graph the greater would be the difference between it and the composite "accelerated fatigue" graph.

In Fig. 7 are shown stress-strain graphs representing the same specimens that are designated by the same letters in Figs. 5 and 6. As shown in Fig. 7, the deflection method does not give even an approximate indication of the endurance limit of duralumin. Whereas in graph *N* the "proportional limit" is about 14,000 lb. per sq. in., in graph *C*, representing an accelerated fatigue test, the proportional limit is about 6000 lb. per sq. in.

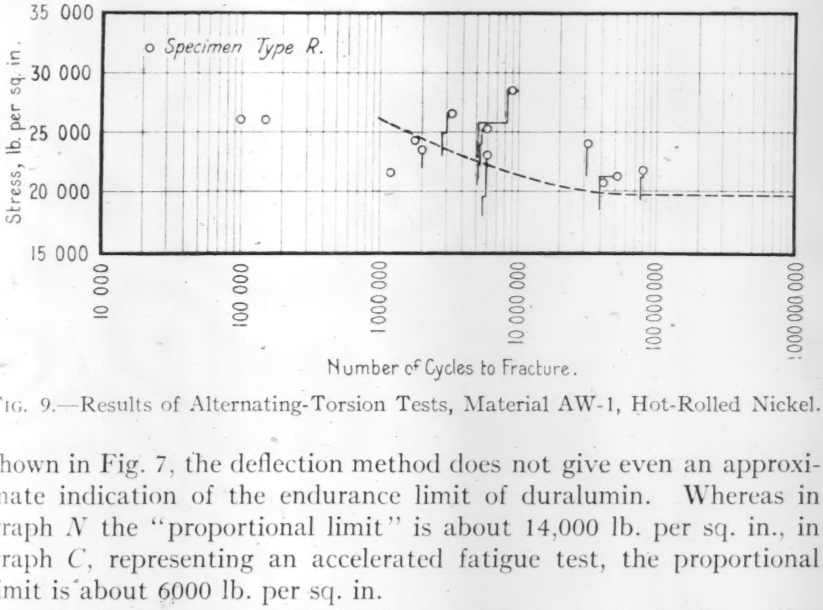

FIG. 9.—Results of Alternating-Torsion Tests, Material AW-1, Hot-Rolled Nickel.

Results Obtained with Nickel.—Results obtained with hot-rolled nickel are illustrated in Fig. 8. As shown in this figure, with an initial stress of 26,000 lb. per sq. in., failure occurred after less than one million cycles. With initial stress of 24,000 lb. per sq. in., failure occurred after several million cycles. With initial stress of 22,000 lb. or lower, failure occurred only after many million cycles, and even then artificial increases of stress were sometimes necessary to cause failure. This would seem to indicate that the endurance limit of this material is about 20,000 lb. per sq. in.

The same results are plotted on a semi-logarithmic scale in Fig. 9. In this figure, automatic increases of stress are disregarded; the vertical lines represent artificial increases of stress. The broken line is an idealized composite graph representing stress-cycle relationship for this material. According to this graph the endurance limit for one billion cycles is only slightly lower than the endurance limit for ten million cycles.

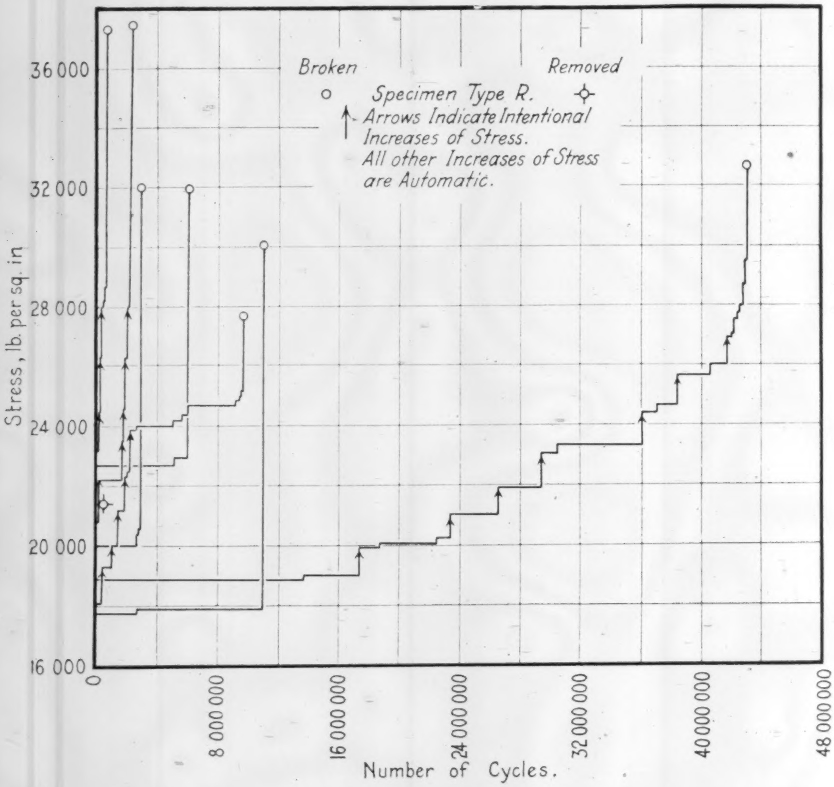

Fig. 10.—Results of Alternating-Torsion Tests, Material AA, Hot-Rolled Monel Metal: Nickel, 66.77; Copper, 29.54 per cent.

Results Obtained with Monel Metal.—Results obtained with hot-rolled monel metal are illustrated in Fig. 10. As shown in this figure, a stress of 28,000 lb. caused failure after much less than one million cycles. As the stress was lowered in successive tests the first part of each graph became flatter. With initial stress of 19,000 lb. or less, one specimen endured many million cycles, and then failed after many artificial and automatic increases of stress; another specimen failed suddenly after about 11,000,000 cycles. Evidently the endurance limit of this material varies from about 17,000 to 21,000 lb. per sq. in. The variation is due to slight non-uniformity of material or to the influence of local concentrations of stress caused by inclusions. A similar range of endurance properties is found by rotating cantilever tests as illustrated by Fig. 12.

The results shown in Fig. 10 are shown on a semi-logarithmic scale in Fig. 11. Automatic increases of stress are not shown in this graph. For comparison with the results obtained by the accelerated fatigue method, four results obtained with an alternating-torsion machine of the spring type are shown in this figure. It will be noted that these four results are consistent with the results obtained by means of the accelerated fatigue method, whereas it might have been expected that the fatigue graph would be above the accelerated fatigue graph. It is possible that in the machine of the spring type there are appreciable frictional stresses that are not measured by the springs. If so, the true fatigue graph should be slightly higher but of approximately the same form.

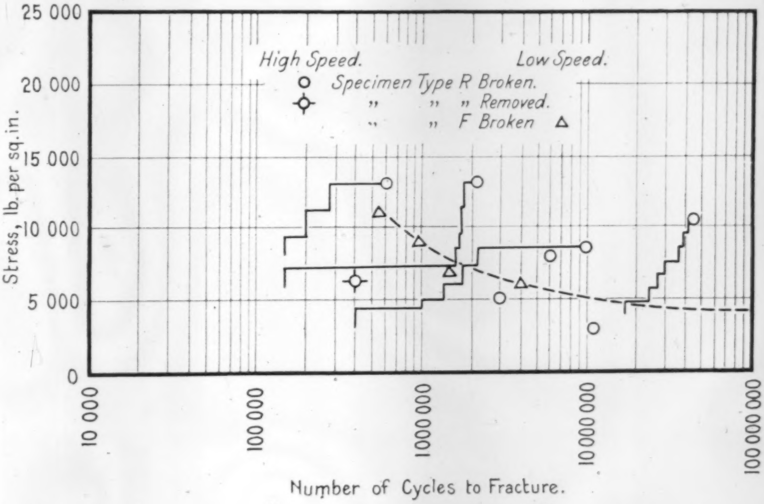

Fig. 11.—Results of Alternating-Torsion Tests, Material AA, Hot-Rolled Monel Metal.

It is of interest to compare the alternating-torsion graph, Fig. 11, with the rotating cantilever graph of the same material as shown in Fig. 12. The alternating-torsion graph is steeper near the beginning and becomes approximately horizontal much sooner than the rotating cantilever graph. Before the experiments with the alternating-torsion machine of the spring type had been made, it was assumed that the difference in form between the rotating cantilever and alternating torsion graphs was due to the effect of fatigue acceleration on the latter graph. Apparently, however, there is an actual difference between the two types of graph that cannot be accounted for by fatigue acceleration. Experiments will be made with other metals to determine whether or not similar differences between the two types of graph exist.

Results Obtained with Copper.—Results obtained with cold-rolled electrolytic copper are illustrated by Figs. 13 and 14. A stress of about 8000 lb. per sq. in. causes failure after less than one million cycles, whereas the material endures a stress of 7000 for many million cycles. The endurance limit of this material is evidently about 6500 lb. per sq. in.

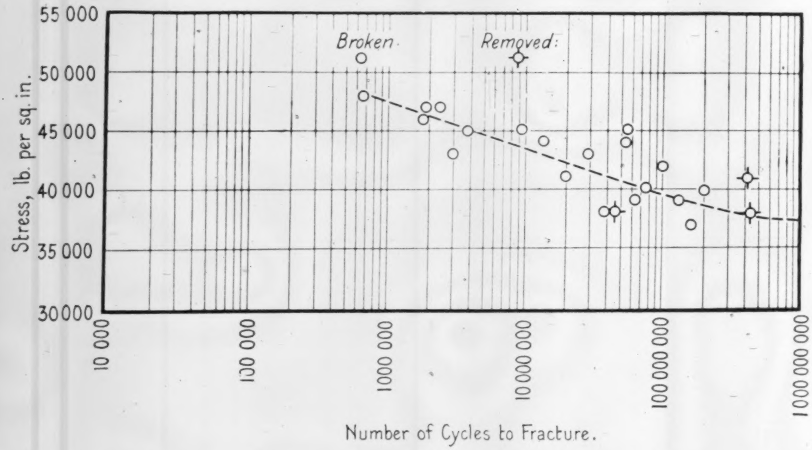

FIG. 12.—Results of Rotating Cantilever Tests, Material AA, Hot-Rolled Monel Metal.

VALUE OF THE ACCELERATED FATIGUE METHOD

As stated above, the form of the graph of a typical accelerated fatigue test depends on the initial stress. If the initial stress is slightly above the endurance limit, the graph near the origin is convex upward. It then becomes horizontal and remains horizontal for a distance that is greater the nearer the initial stress is to the endurance limit. Finally the graph becomes concave upward and increases in steepness until failure occurs. In the part of the graph that is convex upward the strengthening effect of cold working evidently exceeds the effects of fatigue. In the horizontal part of the graph the two effects are apparently in equilibrium. In the part of the graph that is concave upward the effects of fatigue predominate.

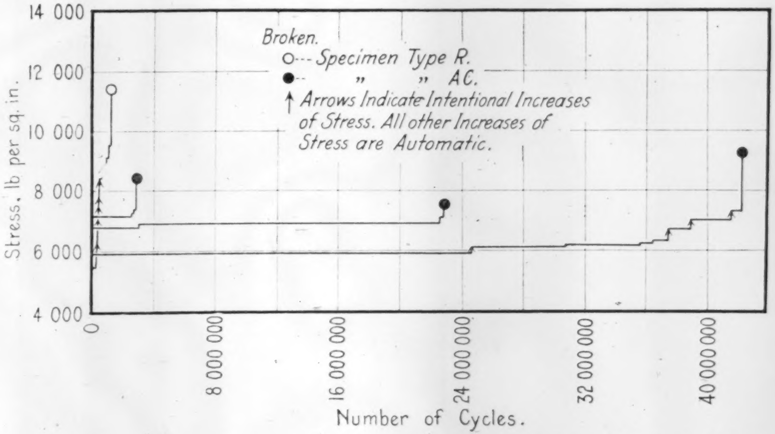

FIG. 13.—Results of Alternating-Torsion Tests, Material BO, Cold-Rolled Copper.

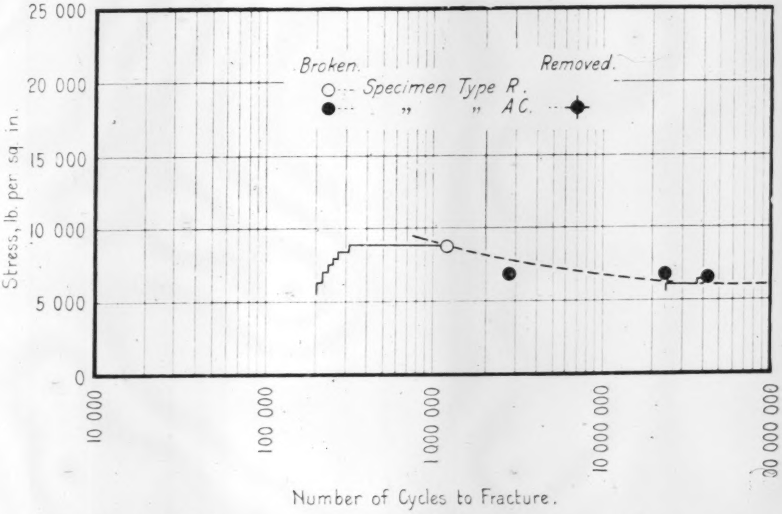

FIG. 14.—Results of Alternating-Torsion Tests, Material BO, Cold-Rolled Copper.

In estimating the value of the accelerated fatigue method in shortening the time of an endurance test, the effect of the part of the graph that is concave upward should probably be given the greatest weight. In a test in which abrupt automatic increase of stress near the beginning is followed by long-continued equilibrium stress, the effect is probably nearly equivalent to that of a test at equilibrium stress from the beginning to the point at which automatic increase of stress again begins, and with the latter part of the test unchanged.

The influence of the automatic increases of stress in the latter part of a test cannot be quantitatively estimated, but it seems evident that a test by this method would require a much shorter time than a test in which the normal stress is held constant. The fatigue acceleration would evidently be greater the nearer the initial stress is to the endurance limit.

It is not necessary, however, to wait until a specimen fails in order to determine whether or not the stress is near the endurance limit. Below a limiting initial stress there is no automatic increase of stress near the beginning of the test. This limiting stress in steel is probably slightly below the endurance limit as determined by a fatigue test. In non-ferrous metals, the limiting initial stress apparently approximates the endurance limit. This will be evident from a study of the graphs in Figs. 5, 8, 10 and 13. If the first part of the graph remains practically horizontal for five or six million cycles, the initial stress cannot be much higher than the endurance limit of the specimen.

ENDURANCE LIMITS OF NON-FERROUS METALS

Investigation of the endurance properties of non-ferrous metals indicates that for each non-ferrous metal there is an "endurance limit" that is practically as definite as the "endurance limit" for steel. The stress-cycle graphs of non-ferrous metals approach a horizontal direction, but usually after many million cycles. The rotating cantilever graphs of some non-ferrous metals, drawn on a semi-logarithmic scale, do not become nearly horizontal before an abscissa of several hundred million cycles is reached. The rotating cantilever graph for copper, however, becomes nearly horizontal at an abscissa of less than ten million cycles.

The alternating-torsion graphs of non-ferrous metals obtained by the accelerated fatigue method become nearly horizontal after only a few million cycles. The rapid approach of the accelerated fatigue graph to the horizontal direction is probably due, in part at least, to fatigue acceleration.

Acknowledgment.—Acknowledgment is hereby made of the encouragement received in this work from Captain P. B. Dungan, U. S. Navy, Officer in Charge, U. S. Naval Engineering Experiment Station. The assistance received in this work from George F. Wohlgemuth, Associate Metallurgist, and from E. A. Snader and A. P. Vandermast, laboratorians, is also acknowledged.

References

(1) D. J. McAdam, Jr., "Endurance and Impact Tests of Metals," *Proceedings*, Am. Soc. Testing Mats., Vol. XVI, Part II, p. 292 (1916).

(2) D. J. McAdam, Jr., "An Alternating Torsion Testing Machine," *Proceedings*, Am. Soc. Testing Mats., Vol. XVII, Part II, p. 599 (1917).

(3) D. J. McAdam, Jr., "A High-Speed Alternating Torsion Testing Machine," *Proceedings*, Am. Soc. Testing Mats., Vol. XX, Part II, p. 366 (1920).

(4) D. J. McAdam, Jr., "Endurance Properties of Steel: Their Relation to Other Physical Properties and to Chemical Composition," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 56 (1923).

(5) H. J. Gough, "Improvements in Methods of Fatigue Testing," *The Engineer*, August 12, 1921.

(6) D. J. McAdam, Jr., "Endurance Properties of Corrosion-Resistant Steels," *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part II, p. 273 (1924).[1]

[For a discussion on Fatigue of Metals, see page 601.—Ed.]

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[1] The present volume.—Ed.

NOTES ON SOME ENDURANCE TESTS OF METALS[1]

By H. W. Gillett[2] and E. L. Mack[3]

Introduction

During the past few years certain endurance tests have been carried out at the Ithaca Field Office of the Bureau of Mines at Cornell University. These were begun before the publication of H. F. Moore's work on the theory and practice of endurance testing, and the early portion of the work was done with the blindness which characterized much endurance testing before the subject was clarified by Moore's epoch-making report.

The work was done with no idea of studying methods of endurance testing, but as part of an investigation of the properties developed in steel by alloying additions of molybdenum and of cerium. However, the portions of the work devoted to endurance testing took on added interest because of the elaborate claims of "fatigue"-resisting properties put forward by those interested in the commercial exploitation of molybdenum.

As the work progressed it appeared that non-metallic inclusions and other inhomogeneities in steel affect the life of the material under repeated stress and the endurance testing was therefore continued with the idea that it might throw light on the relative desirability of clean or dirty steel.

In the course of the work some by-products in the line of methods of endurance testing and of observations of endurance phenomena came to light which appeared to be of some interest as added proof of the correctness of Moore's theory of progressive failure, and he has suggested that they be put on record.

EARLY WORK ON UN-NECKED TEST-PIECES

Through the courtesy of the Sibley School of Mechanical Engineering at Cornell University, there were made available for this work two Upton-Lewis fatigue testing machines for tests under completely reversed bending. These were of the early type (Fig. 1; illustrated by Moore and Kommers(**1**)),[4] in which the upper jaw gripping the test specimen is pivoted on the frame of the machine. In the more recent type the upper jaw is supported only by the specimen and the calibrated springs. This pivot was the least reliable feature of the machine. Any friction in the pivot is added to the resistance of the springs and tends to make the calculated stresses too low, while any looseness makes the reading of the amplitude of motion of the cross-head between the springs so uncertain that the stress calculations are again vitiated.

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[1] Published by permission of the Director of the U. S. Bureau of Mines, Pittsburgh, Pa.

[2] Formerly Chief Alloy Chemist, U. S. Bureau of Mines, Pittsburgh, Pa.

[3] Assistant Alloy Chemist, U. S. Bureau of Mines, Pittsburgh, Pa.

[4] The boldface numbers in parentheses refer to the list of references appended hereto.

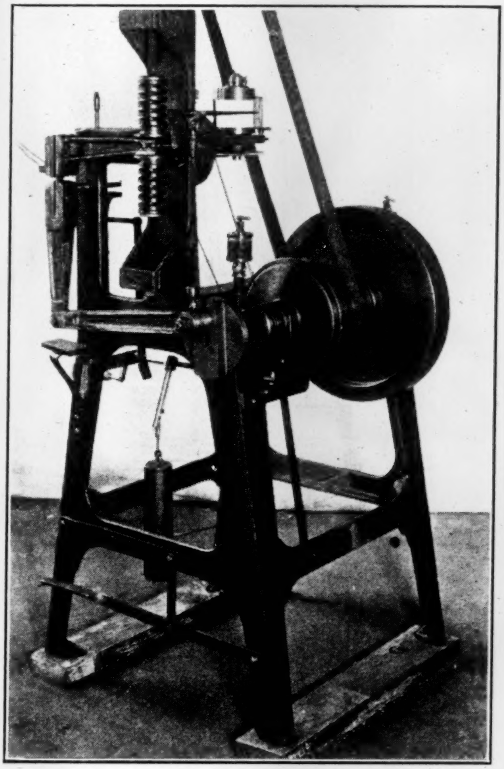


FIG. 1.—Upton-Lewis Endurance Testing Machine.

In the early tests, round un-necked test pieces of about 0.37 in. diameter were used, gripped within the jaws by liners having semicircular grooves closely fitting the specimens. At the points of maximum stress the specimens were thus held tightly against the edge of the liner. It was recognized that increased local stress would be present, but it was thought that comparable results would nevertheless be obtained which would serve to show the relative endurance properties of the different steels. This expectation was not realized in long-time endurance tests, although Upton satisfactorily uses the machine on un-necked flat test pieces for short-time "toughness tests," at stresses well above the elastic limit, for class demonstrations of the effect of heat treatment. But on regular endurance tests the localized stresses at the jaws were too great. About 95 per cent of the un-necked pieces broke at the upper jaw, where the calculated stress is greatest, and about 5 per cent at the lower jaw, where it is least, but none broke in the free test length.

The Upton-Lewis machines were provided with the usual pencil arm for taking paper records of the amplitude of cross-head motion from which to calculate the stress on the specimen. It was soon found that the pencil friction, pencil wear and lost motion in the pencil-arm pivots prevented accurate measurement of stress. Study of many records failed to show any value of the pencil record on long-time tests. The number of cycles covered to the time when the specimen started to fail and the amplitude of cross-head motion decreased gave no more information than the number of cycles to complete failure. For tests running into the millions of cycles only occasional patches of record could be taken without using miles of record paper. On the whole the paper tape records were found to be useless. Ames dials, which could be swung into position against an anvil attached to the cross-head, were then installed so as to read the amplitude of motion directly to about 0.0002 in. by estimation of fifths. The cross-head amplitude was set to give the desired stress on the specimen by adjustment of the movable eccentric or crank-arm. The setting was made by turning the crank-arm over slowly by hand, but since the amplitude was slightly greater when the machine was up to speed, the "running" reading was the one used for stress calculations, since the difference seemed chiefly due to an actually greater cross-head motion and not to over-travel of the dial needle. The distance between the jaws, that is, the free length of the specimen, was set by a gage.

The relations between stress and number of cycles were at first plotted on double logarithmic paper, because it was at first supposed that Basquins(10) straight-line log S - log N relation was a true one for any stress below the static proportional limit and that such curves could be extrapolated from a few tests without having to run to millions of cycles. But the plots of even these early tests show a curvature, and a study of the literature of endurance testing showed that the results of all investigators who had run really long-time tests on steel, plotted on a curve rather than on a straight line, and that the curve tended to become parallel to the N axis.

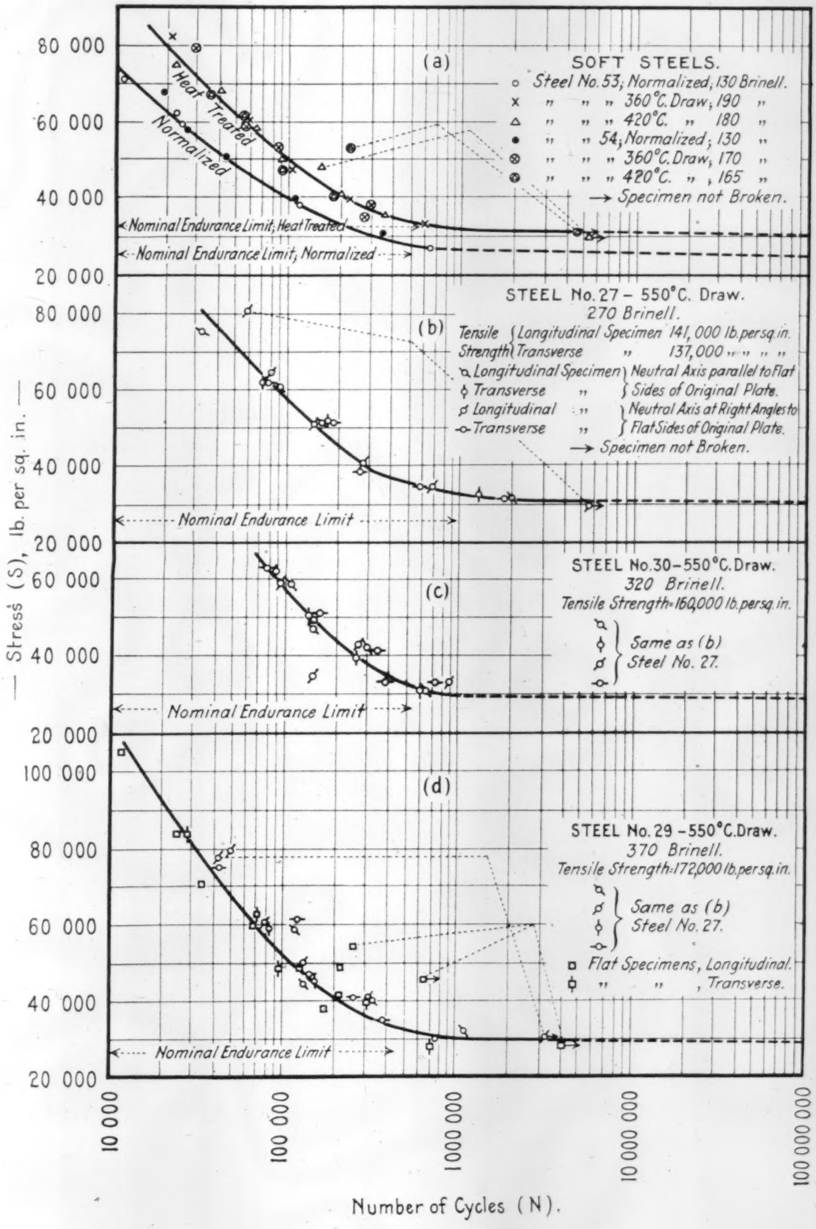


FIG. 2.—Upton-Lewis Endurance Tests on Un-Necked Specimens of Steel.

Points connected by converging dotted lines indicate retesting of unbroken specimens at a higher stress.

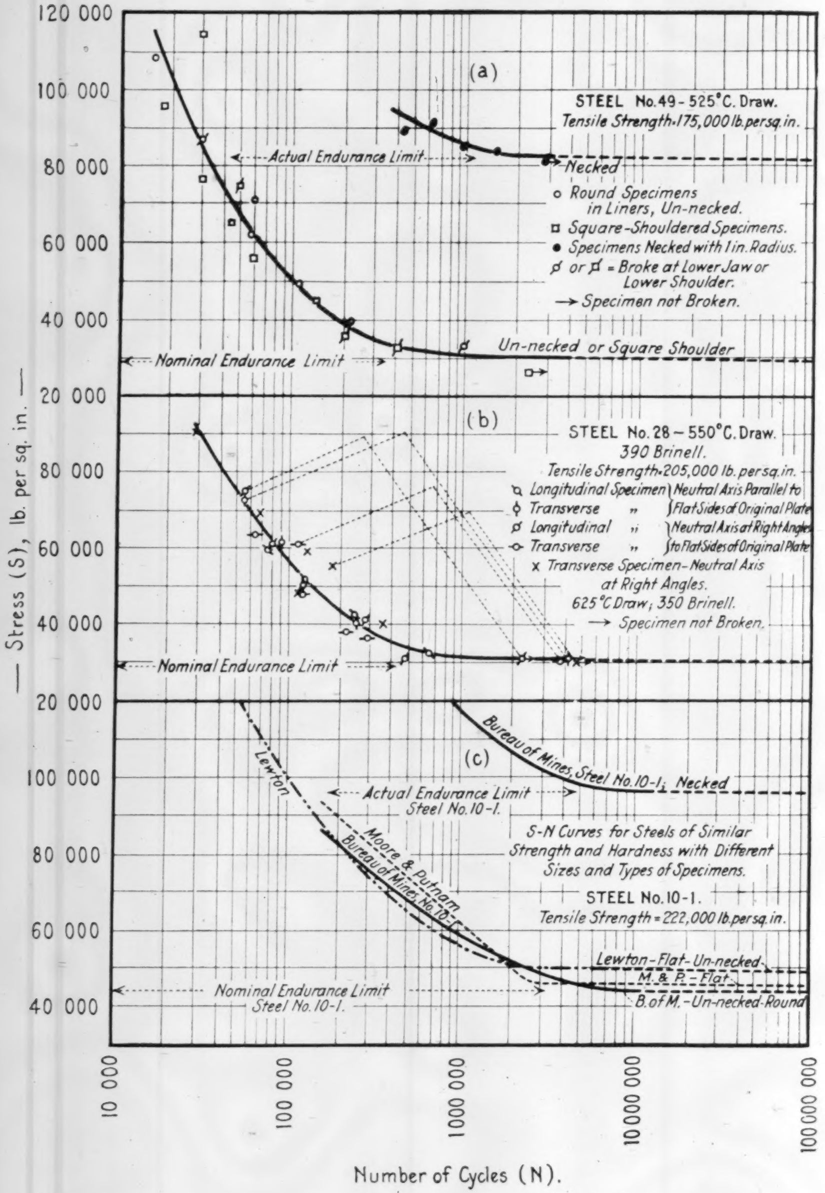


FIG. 3.—Upton-Lewis Endurance Tests on Necked and Un-Necked Specimens of Steel.

Points connected by converging dotted lines indicate retesting of unbroken specimens at a higher stress.

In the later work, stresses of 80,000 to 100,000 lb. per sq. in. were required for many of the steels, and the use of a log scale for *S* crowded the points too closely unless the *S* scale was changed in the plots for different steels. Hence the semi-logarithmic plot was adopted as more convenient.

While the plots showed the existence of an endurance limit very clearly, the un-necked specimens did not sufficiently differentiate between strong and weak steels. For example, the calculated stress at the endurance limit was indicated by the tests as shown graphically in Figs. 2 and 3.

Un-necked flat test pieces gave the same results as the un-necked round ones. Fig. 2 (*d*).

Many other steels indicated an endurance limit of about 30,000 lb. per sq. in., no matter what their strength; only the very softest steels fell materially below this, and only the very hardest materially above it. One of two things seemed certain, either all steel actually had about the same endurance limit or else the localized stress at the jaws affected the harder steels more than the softer ones and brought them all to the same level.

The un-necked test pieces held in the grips seemed to be analogous to a solid piece with a reduced section and having no fillet between the large ends and the reduced section. To test this, steel No. 49 was made up into test pieces having a reduced section of the same size as the free test length of the un-necked round piece between the grips, with the enlarged ends of the specimen taking the place of the testing machine grip liners. On test, these square-shouldered specimens, obviously of very poor design because of the lack of a fillet, gave, as Fig. 3 (*a*) shows, the same results as the un-necked pieces. The un-necked test specimen was thus obviously of faulty form.

Moore and Putnam (4) had previously used in Upton-Lewis tests a flat specimen $\frac{3}{4}$ or 1 in. wide reduced to 0.6 in. wide in the test section by fillets of about $\frac{1}{8}$-in. radius. Their results on a spring steel, plotted in Fig. 3 (*c*), gave an endurance limit of the same order as our un-necked round specimen of spring temper.

More recently Lewton (11) has given Upton-Lewis tests on spring steels using an un-necked flat specimen, and the average curve for his results, which is also plotted in Fig. 3 (*c*), again gives an endurance limit of the same order as found in our work with un-necked test pieces.

Stribeck (12) has recently quoted some results of Lasche on rectangular specimens of steel of tensile strengths varying from 78,000 to 140,000 lb. per sq. in., which gave endurance limits varying from a nominal stress of 27,000 to one of 34,000 lb. per sq. in. Stribeck ascribes this to the gripping of the specimen in a fashion which sets up local excess stress. It will be noted that these figures are again of the same order as those for our un-necked pieces.

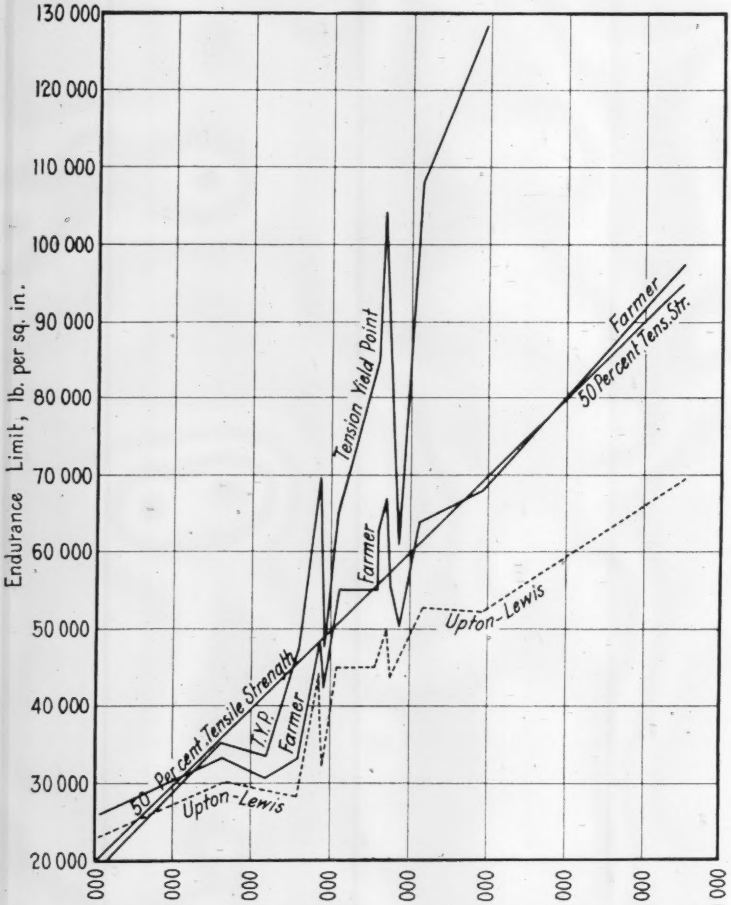


FIG. 4.—Relation Between Tensile Strength, Yield Point and Endurance Limit on the Sondericker (Farmer) Machine and Endurance Limit on the Upton-Lewis Machine, with Improperly Necked Specimens of Steel, from H. F. Moore's Data.

At this stage in the work Moore's data appeared, in which he showed the necessity for the use of an endurance specimen necked down by a fillet of suitable radius (of at least 1 in.) to avoid local stress.

He also used the Upton-Lewis machine, with a flat test piece 1 in. wide necked in from the sides to 0.9 in. with a $\frac{1}{2}$-in. radius and as Fig. 4 shows, he obtained results which do not vary greatly from the rotary bending tests on the softer steels, but which fall well below them on harder steels. Moreover, he found it necessary to reduce his hardest specimen for rotary bending on the Sondericker (also known as the Farmer) machine to a smaller diameter than in the case of the softer steels, to avoid breaking at the collets, indicating that the effect of local stress is greater in the harder steels.

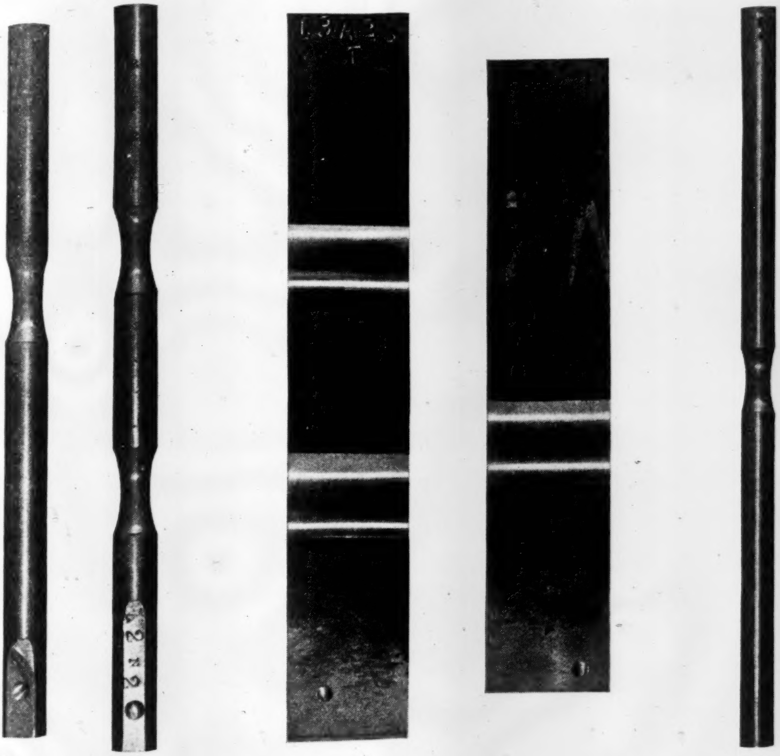


FIG. 5.

(*a*) Upton-Lewis Endurance Test Piece, Round (Half Size).

(*b*) Upton-Lewis Endurance Test Piece, Flat (Half Size).

(*c*) Rotary Bending Endurance Test Piece, Round, for Copper and Brass, ($\frac{3}{8}$-in. Size).

On account of the limitations of the Upton-Lewis machines as to free length of specimen between the jaws, it was impossible to use the 10-in. radius Moore used on his rotary bending test pieces, or the 5-in. radius his tests indicated to be sufficient.

The machines would readily take a $\frac{2}{3}$-in. free length, and our $\frac{3}{8}$-in. diameter bar stock, ground down to 0.350 in. in diameter over the whole length and necked down to 0.2300 in. diameter on a 1-in. radius, gave 0.667 in. as the length of the chord of the neck of the test specimen. This specimen (Fig. 5 (*a*)) has the same ratio between cross-section of shank and cross-section of neck as Moore's 0.40–0.27-in. test piece which he found suitable for his strongest steels or the 0.625–0.43-in. specimen used on his later tests of combined tensile and bending stresses. The latter were necked with a 1-in. radius and Moore found that in plain bending tests these gave almost the same results as his 10-in. radius specimens. He states that the 1-in. radius specimen gives results only 1 or 2 per cent low.

After trying out a $\frac{1}{2}$-in. radius which we found to give results still too low, we adopted the 0.35–0.23-in. by 1-in. radius specimen, which gave results for endurance limits on steels of different tensile strengths that agreed well with Moore's results with the Sondericker machine.

Having thus gone through a time-consuming period of experimenting with specimen design and experiencing the same difficulties that Moore encountered, we utilized his solution of his problem for the solution of ours, and it then seemed feasible to use the Upton-Lewis machine on necked specimens and get results that would mean something in the comparison of the endurance properties of our different steel compositions.

In later work it became necessary to test some flat stock $\frac{1}{4}$-in. thick. Since merely reducing the width of the specimen by cutting it down on the narrow sides had not given satisfactory results in the Upton-Lewis tests of Moore and Putnam(4), Moore and Gehrig(5) or Moore and Kommers(1), it was decided to neck the piece down on a 1-in. radius on the *wide* side, in the line of the applied stress. These pieces were hence necked down on a 1-in. radius to a thickness of 0.135 in. at the middle of the neck, which gave the same 0.667-in. length of the chord of the neck as on the round specimen. These specimens are shown half size in Fig. 5 (*b*). With steels of less than 270,000 lb. per sq. in. tensile strength, neither of these specimens break at the jaw, but in a few cases, with still harder steels, they have done so. The effect of localized stress at the jaw is so great in these very hard steels that a still thinner neck or a larger radius would be needed.

STRENGTHENING BY UNDERSTRESSING

The work on un-necked specimens had shown nothing as to the relative endurance of different steels. It did, however indicate the greater vulnerability of the harder steels to local increase in stress and indicated that at some stress, whatever that might actually be on account of the local stress at the jaws, there was an endurance limit, and that this was shown by a "knee" in the S-log N curve at approximately one million cycles. On a few specimens stressed just below the endurance limit for a few million cycles, after which the stress was raised and the test continued, it was found (see Fig. 2 (*d*)) that the specimen showed a decidedly longer life at the higher stress than did a duplicate specimen tested initially at the higher stress. The strengthening effect of understressing was thus evident from these early tests.

EFFECT OF NON-METALLIC INCLUSIONS

Another point drew our attention in the early work. When a test piece showed a longer life than the average curve called for at the nominal stress, microscopic examination of an unetched surface taken as close to the fracture as possible, would generally show a rather clean steel, while with one showing a shorter life than the average curve indicated, examination was likely to show many non-metallic inclusions. The dirtier steels seemed to be less reliable than the cleaner ones.

Much work was done on this point and while the bulk of the evidence indicated that a clean steel gave better results, the opposite often appeared to be the case, and we came to the conclusion that it was next to impossible to polish the surface of a fractured specimen and show the actual nucleus of fracture. In polishing, some of the material is removed and the evidence thus destroyed, so that all the examination shows is whether the steel is clean or dirty at a point more or less remote from the actual point of maximum stress at which fracture started.

Examination of successive surfaces showed that the distribution of non-metallic inclusions is so extremely non-uniform that unless tedious study of many surfaces indicates that the specimen is uniformly very clean or very dirty, it is quite impossible to say that the steel was clean or dirty at the actual point of fracture.

By giving the specimen a sufficiently fine metallographic polish to show inclusions on the surface before making the endurance test and then examining it after breaking, it might be possible to get more definite proof, but to secure such a polish on a necked specimen is very difficult, and there is too much uncertainty as to the actual stress in un-necked specimens to make it worth while to work with them.

WORK WITH NECKED SPECIMENS

SURFACE FINISH

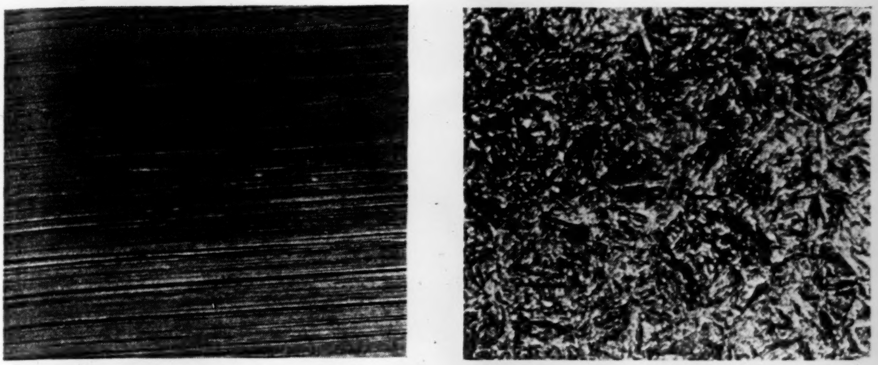
Both the necked and un-necked test pieces were polished to remove all scratches running around the neck and to leave only those running lengthwise. It was noted that the early results of McAdam (7) generally indicated a slightly lower endurance limit than those of Moore on steels of similar tensile strength. This may be due to the greater area stressed in the tapered McAdam test piece and the consequent greater chance for inclusions to show an effect. Examination of specimens kindly sent us by both Moore and McAdam showed that those of Moore, while not entirely free from circumferential scratches, were relatively so in comparison with the early ones of McAdam, which were finished by polishing with the specimen rotating. Later work of McAdam (9), illustrated in his Figs. 7 and 8, in which he has compared longitudinal and circumferential polishing, indicates slightly higher average results with the longitudinal polish.

Aitchison (30) and Jenkin (26) show that, according to the theory of the development of local overstress, scratches that run across the line of stress may be fatal, while those that run with the line of stress have no effect. Hence the necked round specimens were polished in the neck portion in such a manner that the marks ran in the direction of the longitudinal axis of the specimen. The abrasives successively used for polishing were No. FF Three-M-Ite cloth and Nos. 0, 00, and 000 Hubert emery paper. Plate I (*a*) shows, at 100 diameters, the average finish at the middle of the neck.

After polishing, the diameter at the minimum section of the specimen was measured with a micrometer having rounded spindle and anvil to avoid marring the polished surface. The specimens were then coated with slushing oil to prevent rusting.

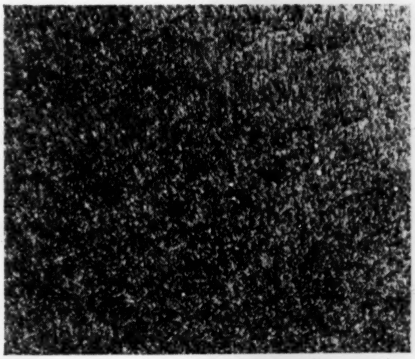
PROCEDURE IN TESTING

The Upton-Lewis testing machines were adjusted to give as nearly as possible equal tensile and compressive stresses, that is, completely reversed stress. The equality is doubtless less perfect than in a rotary bending test, but Moore (2) showed that 10 per cent inequality has but slight effect, and McAdam came to the same conclusion in regard to reversed torsion tests. The machines were run at from 480 to 680 r. p. m., the usual speed being 525. Within these limits no effect due to difference in speed was noted. Tests run partly on one machine and partly on the other agreed as well as those run wholly on one machine. The Brinell hardness number of every endurance specimen was taken and the agreement between duplicate

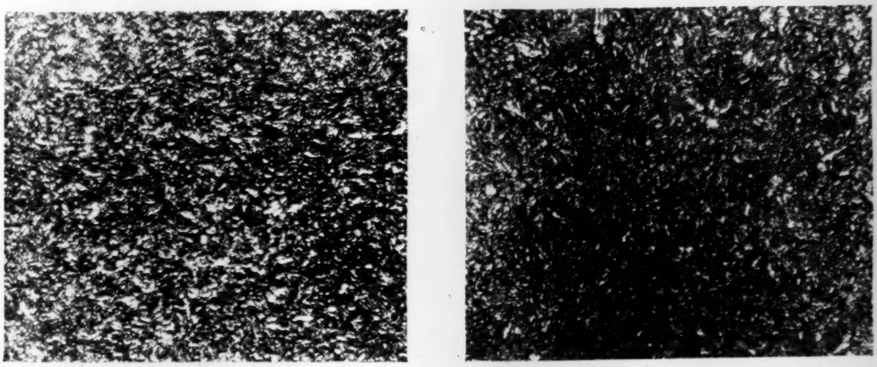


(*a*) Surface appearance of necked endurance test piece at point of minimum section (× 100).

(*b*) Microstructure of steel No. 50. C, 0.52, Cr, 0.95, Mo, 0.39. Draw 400° C. (750° F.) (× 500). Tensile strength, 210,000 lb. per sq. in. Endurance limit, 100,000 lb. per sq. in.



(*c*) Microstructure of steel No. 44. C, 0.36, Mo, 3.00. Draw 575° C. (1065° F.) (× 150). Tensile strength, 177,000 lb. per sq. in. Endurance limit, 115,000 lb. per sq. in.



(*d*) Microstructure of steel No. 26. 1 hr. draw at 525° C. (975° F.) (× 500). Brinell, 420. Endurance limit, 87,000 lb. per sq. in.

(*e*) Microstructure of steel No. 26. Drawn 1 hr. at 430° C. (805° F.), re-drawn 2¼ hr. at 525° C. (975° F.) (× 500). Brinell, 420. Endurance limit, 123,000 lb. per sq. in.

PLATE I.—Surface Appearance and Microstructure of Certain Steels.

pieces was usually within the limit of error in making Brinell hardness readings.

The location of the fracture was always noted. The test piece should break at the middle of the neck. When it breaks above or below the middle, the stress at the fracture is less than that calculated for the specimen, while the most highly stressed portion is still unbroken. There seems to be no better way to plot such results than for calculated maximum stress and actual life, but all such points are noted on the plots for necked specimens by drawing a diagonal line through the point. Endurance tests of steels having low endurance limits usually show, on graphic representation, not only a wider "scatter" than a good steel, but also more specimens breaking at points other than that of minimum section. The presence of local "stress-raisers" probably is indicated when this type of break is obtained.

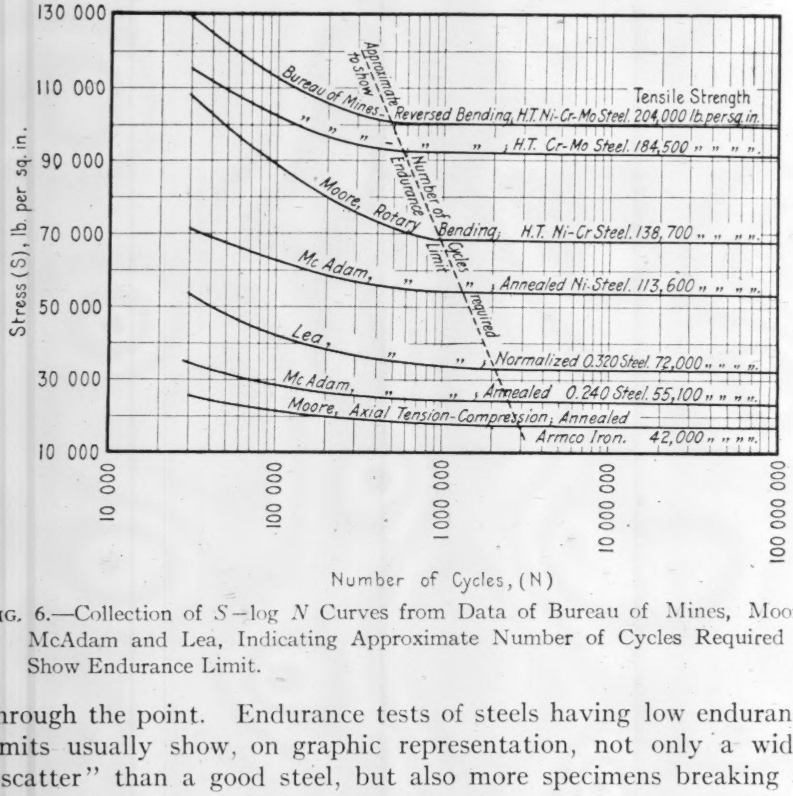


FIG. 6.—Collection of $S-\log N$ Curves from Data of Bureau of Mines, Moore, McAdam and Lea, Indicating Approximate Number of Cycles Required to Show Endurance Limit.

CHOICE OF LIMITING NUMBER OF CYCLES

It has been stated that in the early tests on un-necked test pieces the "knee" of the S-log N curve appeared at approximately one million cycles. Moore and Kommers(1) always found the "knee" in their Upton-Lewis tests at not over a million cycles and ran their tests to only two million. A study of McAdam's data shows that in 85 per cent of his tests the same figure for endurance limit would be found if the tests were stopped at one million instead of 10 million, while in the other 15 per cent the stress at a life of one million would be perhaps 2000 lb. per sq. in. higher than that found with 10 million as the criterion. A similar study of Moore's(1, 2) data shows that on the Sondericker test 78 per cent would give the same endurance limits as he finds by running to 10, to 100, or to 200 million, were the tests run only to one million. In 18 per cent the stress at one million is within 2000 lb. per sq. in. of the endurance limit while in 4 per cent it is slightly greater.

Moreover, in both McAdam's and Moore's tests, the steels which require that the tests be carried beyond one million cycles are soft, low-carbon or annealed steels of relatively low tensile strength. Heat-treated alloy steels always show results very close to the actual endurance limit by tests to a million cycles, if a reasonable number of specimens are tested so as to minimize the effect of accidental variations in the specimens themselves or in the method of testing.

When endurance results for steels of different tensile strength are compared as to the number of cycles required to locate the "knee" of the curve, we get a family of curves such as is shown in Fig. 6, which indicates fairly clearly that, on a 200,000-lb. tensile-strength steel, one-half million cycles will generally show the endurance limit and on the softest, 40,000-lb. steel 3 million cycles are adequate. The harder, quenched-and-tempered steels give a sharp "knee" while the softer ones give a flat "knee", probably because of the location of the yield point in relation to the endurance limit. It might be pointed out that many non-ferrous alloys give curves much like that for Armco iron in which the "knee" is not sharp and in which many millions of cycles will be required to show whether an endurance limit exists or not. The short cuts that seem usable on wrought ferrous metals cannot yet be extended to cast materials or to non-ferrous alloys. McAdam(13) shows a quite similar family of curves for tests in reversed torsion. These were made at high stresses and short lives, but indicate a similar gradation from hard to soft steels.

Both Moore(2) and McAdam(9), after studying the phenomena of endurance in tests running to many millions of cycles, sometimes to a billion, now appear satisfied with tests to no more than 10 million for steel.

In the most carefully made endurance tests the absolute value of the endurance limit is somewhat in doubt, due to lack of absolute straightness of specimens, lack of perfect alignment of bearings, inaccuracy of spring calibration, and other difficulties of testing, and Moore(3) now refers to a "range of values." When we consider that a 5-per-cent variation in tensile strength or proportional limit among multiplicate specimens is by no means unusual in fairly refined tension testing, and that 5-per-cent variation in stress near the endurance limit means perhaps 500 per cent difference in life, the discrepancies found in endurance testing are to be expected, especially when the profound effect of local "stress-raisers" is kept in mind.

From the engineering point of view, some factor of safety is required, and a factor of safety based on tests of a hard steel to one million cycles instead of to 10 million would appear satisfactory.

The number of cycles required to show the "knee" might be expected to vary somewhat with the type of test piece and with the speed, but for any given method of testing, after preliminary tests carried to many million cycles on a few different types of steel, it would appear that the number of cycles required might be safely interpolated for other steels.

USE OF THE PHENOMENON OF STRENGTHENING BY UNDERSTRESSING

While it appears that on the Upton-Lewis machine, at least, it is fairly safe to stop a test after a hard steel has undergone a million stress cycles, or a soft one two million, unbroken, it seems safer to corroborate the result by raising the stress and running the specimen to failure.

Moore(1,2,3) has shown that steel stressed above the endurance limit is progressively damaged. If incipient damage has begun, that is, if a crack is in process of development, raising the stress should hasten failure. Hence a piece which has run a million cycles without a failure but which is nevertheless damaged and might fail at 10 millions, should show a shorter life on retest at a higher stress than would a virgin specimen. Overstressing damages the material.

On the other hand, the early tests on un-necked pieces showed that stressing below the endurance limit strengthens the specimen so that it will last longer at a stress above the limit than a virgin specimen. Understressing improves the material. Many observers (2,9,15,16,17,18,19) agree on this point though the exact mechanism of the improvement is still not entirely clear. Gough and Hanson(52) offer a plausible explanation by experiments indicating that slip may take place on certain planes, thus strengthening those planes, on the tension half of the cycle, and on *other* planes on the compression half.

Instead of merely shifting the range in each half-cycle and shifting it in the other direction in the other half-cycle, the range may thus be extended. This would explain not only the cases where the endurance limit lies above the primitive static proportional limit, but the strengthening phenomenon as well.

Lea(14) terms understressing and progressively raising the stress, "coaxing."

Moore's latest work(3) even shows that damage from slight overstressing can be partly repaired by understressing.

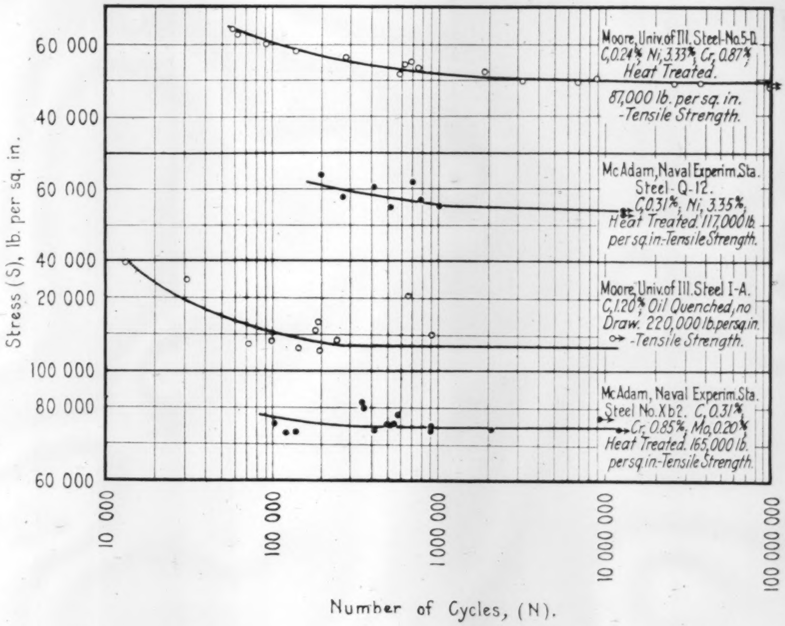


FIG. 7.—Endurance Test Data Taken from Report of Moore and McAdam. The curve with the smooth "knee" seems to express fairly well the representative data of these two investigators.

LOCATING THE ENDURANCE LIMIT BY COAXING

The endurance limit is, then, a computed or statistical stress at which no local point in the test piece is under sufficient local stress to start a crack, and at which the strengthening effect predominates. The ability of a specimen to be strengthened by understressing therefore appears, at least in steel, to be a criterion by which we may determine whether the stress corresponding to the endurance limit has been exceeded.

If a piece unbroken at a million cycles on hard steels, or two million on softer steels, is tested at a higher stress and fails at a shorter life than a virgin piece (which very seldom happens) it would appear that the original stress was slightly above the true endurance limit. If it lasts decidedly longer than a virgin piece (which usually happens) it affords evidence that it would have lasted longer, and probably indefinitely, at the original stress. As examples of the latter case may be noted steel No. 2, draw 3 (Fig. 9), and of the former case Brass No. 1 (Fig. 19).

It is recognized that this accelerated method of testing involves the assumption that there is a real correlation between the results thus obtained and those given by long-time life tests at unaltered stresses. The data presented make this assumption appear plausible in the case of steel specimens. It is still unproven in the case of other alloys.

Table I.—Showing Strengthening Effect of Understressing.

Steel No. 2.—C, 0.41; Mo, 0.67. Normalized. 225 Brinell

Stress, lb. per sq. in.	Life, Number of alternations	Remarks
60 000	276 000	Broke at middle of neck.
57 000	26 900	Broke slightly below middle.
55 000	1 137 000	Broke below middle.
54 500	2 472 000	Not broken, stress raised.
61 500	1 059 000	Not broken, stress raised.
72 500	206 000	Broke at middle.
Steel No. 24.—C, 0.40; Ni, 2.52; Cr, 0.84; V, 0.20. Draw 1. 420 Brinell		
109 000	61 500	Broke at middle.
106 000	273 000	Broke at middle.
101 000	187 000	Broke slightly above middle.
98 500	1 172 000	Not broken, stress raised.
109 500	313 000	Broke slightly above middle.
96 000	944 000	Not broken, stress raised.
103 000	1 097 000	Not broken, stress raised.
113 000	110 000	Broke at middle.
106 000	1 164 000	Not broken, stress raised.
109 500	1 476 000	Not broken, stress raised.
115 000	590 000	Broke at middle.

Endurance testing is so time-consuming at best that every legitimate means of shortening the time required must be utilized in routine testing.

In our tests, then, if a specimen did not break in 1 or $1\frac{1}{2}$ million cycles, without removing the piece from the machine, the stress was raised 5 or 10 per cent and the test continued. If the piece withstood another 1 to $1\frac{1}{2}$ million, the stress was again raised and so on till fracture finally occurred. The higher stress points are merely corroborative of a probable longer life at the lowest stress, and these higher stress points must be disregarded in plotting the curve. Such points in our plots are connected by lines meeting at a common point.

The S-log N curves give examples of the strengthening effect of understressing. Characteristic examples are given in Table I.

GRAPHIC REPRESENTATION OF DATA

It will be noted that in Fig. 6, the type of curve drawn does not agree with that used by some of the investigators whose results are plotted. Moore(1,2,3) uses two straight lines, one sloping, and one horizontal, with a sharp "knee" at the junction. McAdam(9) now draws only the horizontal line, and, on account of the "scatter" of points just above the endurance limit, does not draw in the high-stress branch of the curve at all. The authors were forced to draw a smooth "knee" and not a sharp one to express the results on un-necked test pieces (Figs. 2 and 3) and as Fig. 7 shows, such a curve seems to express fairly well the representative data of Moore and McAdam.

Our curves are drawn with the low stress end not absolutely horizontal, which may not appear to agree with our belief that there is a true endurance limit for any particular test specimen of wrought steel. This type of curve, however, does agree with McAdam's statement that "there is a continuous curvature (on a semi-log plot) as the stress decreases until the diagram becomes a straight line with slight downward slope." A curve of very slight slope may or may not become horizontal at billions of cycles, and from the engineering point of view, it is immaterial whether it does or not. We have drawn the curve with a slight slope from the "knee" to the 100-million-cycle point because in actual testing, fractures sometimes occur at 50 million or more cycles, as in Moore's steel No. 5 D (Fig. 7). Lea(14) also had fractures at 40 to 80 million cycles, and the type of curve we have used, with a slightly slanting line below the endurance limit, fits his data. Variations in surface finish, or the chance presence of an inclusion at the crucial point of an occasional specimen, make it almost certain that if enough specimens are tested right at the average endurance limit, some will fail at a life greater than 1 or 10 million. Moore (2) had one failure at 948,019,300 cycles.

The S-log N curve is very analogous to a stress-strain curve for static proportional limit. The more delicate the method of measuring strain, the lower the indicated proportional limit. Yet a fairly insensitive extensometer (corresponding to an endurance life test of a million cycles) will compare different steels well enough for most purposes and will place them in about the same order as the most delicate extensometer (corresponding to an endurance life test of 100 million cycles).

ACCELERATED ENDURANCE TESTS

Coaxing Method.—A fairly rapid method for determining the endurance limit results from starting a series of tests at the average endurance limit predicted from the tensile strength or Brinell hardness (or from such a curve as Fig. 13) and running only to one or two million cycles, depending on whether the steel is hard or soft and checking up by raising the stress, if the specimen remains unbroken.

Magnetic Method.—Fraichet (20) has studied the magnetization of various steels while undergoing a tension test. He finds a break in the stress-magnetization curve at a stress below the static proportional limit, and since he considers that this break in the curve denotes the first permanent molecular deformation, he calls it the "true elastic limit." He believes that it still remains to fix the relation existing between this "true elastic limit" and the fatigue limit. Since he finds this "true elastic limit" to vary between 25 and 60 per cent of the tensile strength, it seems unlikely that it tells anything definite about the fatigue limit.

Moreover he finds that sound specimens of cast steel show exactly the same "true elastic limit" by magnetic study, as do flawed specimens which break prematurely in the tension test because of the flaw.

Elastic Range Method.—Smith (19) studied the changes in the elastic range of a piece stressed both in static tension and under a superimposed alternating load, but the testing machine used was of a type incapable of giving very trustworthy results. Nevertheless the elastic ranges found by his method seemed to approximate the endurance range as found by rotary bending tests. Smith's method is a difficult one to handle experimentally, especially in testing with completely reversed stress, and does not appear to have been developed farther.

Francke (21) used an excessively delicate apparatus for static flexure tests and found breaks in the stress-strain diagram below the tensile proportional limit which he termed fatigue limits. Comparative tests of this apparatus on steels on which Moore had determined the endurance limit by the rotating beam test showed (1), on six steels, four cases of agreement within 3500 lb. per sq. in., but in one case the Francke point was 11,000 lb. per sq. in. high and in one 6000 lb. per sq. in. low.

Rise-of-Temperature Method, Calorimetric.—Stromeyer (22, 23) used a calorimetric method for determination of the endurance limit in alternating torsion tests, the principle being that, up to the endurance limit, action is elastic while at the endurance limit inelastic action begins, and heat is generated in the specimen.

Rise-of-Temperature Method, Thermometric.—Gough(24) also used a more delicate method in which the rise of temperature at the endurance limit was detected by a differential thermocouple with results that appear to agree moderately well with endurance limits found by fracture tests. Moore and co-workers have developed the rise-of-temperature method farther than other workers, and find(2) very close agreement between endurance limit by rise of temperature test and by rotating beam tests.

The advantage of a reliable and rapid method for determination of the endurance limit would be so great that an attempt was made to apply the rise of temperature method to the Upton-Lewis tests on round specimens. Moore found(1) little difficulty in securing satisfactory data by this method on specimens subjected to rotary bending. On attempting to apply Moore's procedure to tests made under reversed bending on the Upton-Lewis machine we had great difficulty in obtaining data of value. This was thought to be due, at least in part, to the smaller areas subjected to maximum stress by this test and consequent smaller heat effect produced by incipient failure. It was found necessary to conduct the work in a constant-temperature room and to carefully insulate both test piece and galvanometer against even minor variations in air temperature. The temperature rise under successive increments of stress was measured by a Leeds & Northrup Type 2285*a* high sensitivity galvanometer through a differential copper-constantan thermocouple. The hot junction of the couple was held by a clamp in contact with the specimen at the exact point of maximum stress and the cold junction was taped in close contact with the projecting end of the specimen, but electrically insulated from it by thin paper. Galvanometer deflections were read by a mirror and scale system whose characteristics were such that one scale division represented a temperature rise of 0.0018° C. Special precautions were found necessary to insure critical damping of the galvanometer and to eliminate the effect of "zero drift" of the instrument.

Experiment showed that 1000 stress cycles (occupying about two minutes) gave the maximum temperature rise, so that all tests were made with 1000 stress cycles, unless otherwise noted. The maximum temperature rises noted were of the order of 0.02° C.

On repeating a test on a given specimen, the slope of the straight portion of the stress-galvanometer deflection curve was usually found slightly greater than on the original test, but the first break in the curve was usually duplicated within about 2000 lb. per sq. in. Tests on duplicate specimens usually agreed within 4000 lb. per sq. in. in

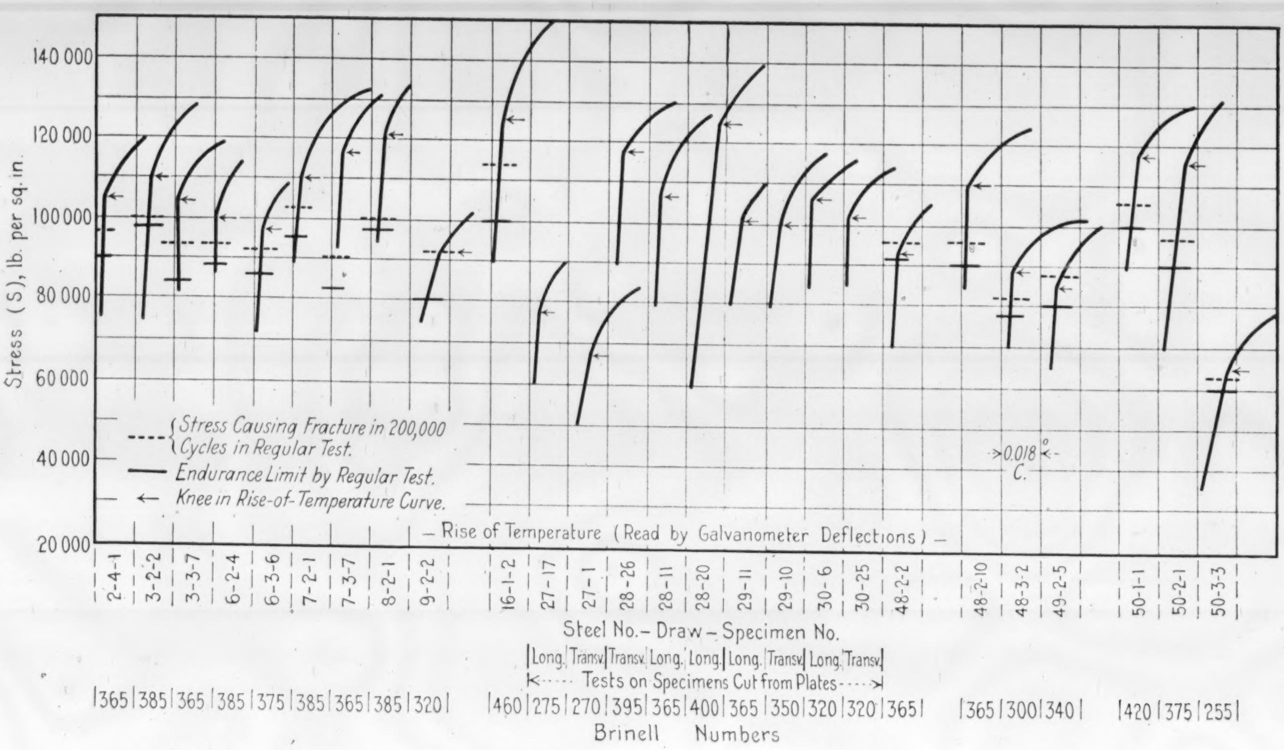


FIG. 8.—Rise-of-Temperature Tests on the Upton-Lewis Machine, Necked Round Specimens of Steel.

locating the break in the curve. In the case of some very hard steels discrepancies as high as 15,000 lb. per sq. in. were found. The break in the stress-galvanometer deflection curve was fairly sharp in most cases.

Some of the data obtained by this method are presented in graphic from in Fig. 8. In this figure are compared the location of the break in the stress – temperature rise curve, the endurance limit shown by Upton-Lewis life tests, and the stresses in the neighborhood of the break in the stress – temperature rise curve which caused failure at 200,000 cycles in actual life tests. That the break in the stress – temperature rise curve would locate the endurance limit too high is obvious, not only from comparison with the results of the Upton-Lewis life tests but also by the short life shown at stresses corresponding to the break in the stress – temperature rise curve.

It was concluded that, for the Upton-Lewis test on round necked specimens, no correlation could be made between the break in the stress – temperature rise curve and the true endurance limit. As previously intimated, this failure may be due to the exceedingly small heat effect produced by the small volume subjected to stress in the case of the round test pieces. Other tests subjecting larger volumes of metal to maximum stress may justify other conclusions regarding the usefulness of the rise-of-temperature test. The conclusions of other investigators who have worked with rise-of-temperature tests are substantially in accord with that reached by us. Attempts to apply Moore's method to duralumin gave results(25) twice as high as those found by actual life tests, presumably because the high thermal conductivity of duralumin dissipated so rapidly the heat generated by incipient failure as to prevent even approximate location of the endurance limit. In monel metal, Moore(3) finds that the first indication of failure by the rise-of-temperature method is at a stress at which the piece will fail in a short time under life tests. Jenkin(26) believes that the rise-of-temperature test cannot be relied upon without discrimination.

Plans to further investigate the rise-of-temperature test on flat necked test pieces were abandoned when Moore reported(3) cases in which steel "after a few thousand cycles of stress, became appreciably hot and then after some millions of cycles of stress (with no interval of rest) became cool again and ran out to 100 million cycles without failure."

Change-in-Rate-of-Deflection Method.—Several experimenters have attempted to find a rapid method of detecting the change in properties at the endurance limit by other methods. Gough(24) and Lea(14) independently devised machines by which, through the use of very sensitive optical levers, changes in the rate of deflection of the specimen with different loads may be determined while the bar is rotating. Means are provided for varying the load while the test is in operation, without stopping the machine.

Robson(20) describes a testing machine, designed by Raven, using either of two types of mechanical deflectometers, one sensitive to $\frac{1}{5000}$ in., the other to $\frac{1}{15000}$ in. He gives the stress-deflection curves for a mild steel of 55,000 lb. per sq. in. tensile strength showing a break at 31,800 lb. per sq. in. which is taken to be the endurance limit. This is 58 per cent of the tensile strength. A similar curve for a steel of 90,500 lb. per sq. in. tensile strength gives a break at 39,800 lb. per sq. in. or 44 per cent of the tensile strength. He states that mild steels have a relatively higher fatigue limit than harder ones. Moore(1) found this to be the case for Armco iron, but McAdam tested an annealed 0.24-per-cent carbon steel of 55,000 lb. per sq. in. tensile strength and found the endurance limit at 22,500 lb. per sq. in. or 41 per cent by tests made in the conventional way.

Templin(28) tried the change-in-rate-of-deflection method in tests on duralumin and other aluminum alloys, and could detect no change in rate of deflection, even above the static proportional limit. He used a less sensitive deflectometer than the other investigators cited.

Lea(14) says that the deflection method, with a sufficiently sensitive optical deflectometer, gives the fatigue limit for some metals quickly but the tests require great care and the specimens should not be overstresses and then tested.

Gough(29) applied his deflection method to annealed copper, and found a "knee" in the stress - cyclic deflection curve at 12,300 lb. per sq. in. In breaking tests a specimen stressed to 11,800 lb. per sq. in. was unbroken after 9,760,000 cycles. The stress was then raised to 13,450 lb. per sq. in. and the specimen broke after 1,620,000 cycles. Another specimen was stressed to 16,200 lb. per sq. in. for 348,000 cycles and the stress - cyclic deflection curve taken. The "knee" was found at 12,400 lb. per sq. in. practically the same as was found on a virgin specimen. This overstressed specimen was then given further test at 11,500 lb. per sq. in. and broke after 900,000 cycles. That is, the piece had been so damaged by the overstress at 16,200 lb. that it failed in less than a million cycles at a stress about 7 per cent below the "knee" in the stress - cyclic deflection curve. These accelerated tests appear inadequate to disclose the presence of an incipient nucleus for failure due to overstressing, or that of local "stress-raisers" which may act as such nuclei. One is tempted to say that they show, at best, only the stress at which slipping occurs quite generally in the crystals of the specimen.

The accelerated tests so far described in the literature do not appear to be developed far enough to be reliable substitutes for a series of life tests. Some modifications now being developed may prove to be acceptable.

There are many uncertainties in endurance testing, but as a basis for engineering design there is a degree of certainty in a test in which a spring steel is unbroken after a million cycles of stress, or a soft steel unbroken after 5 million cycles, which is lacking in the present accelerated tests. Of course an endurance limit determined in completely reversed rotary or reversed bending must be modified if the engineer is to deal with incompletely reversed stress, or with axial loading or torsion loading instead of bending, and there is uncertainty in the conversion of test results obtained under one set of test conditions to another set, or to practice. There is little profit in adding another uncertainty by the use of accelerated tests as long as they are of doubtful value. There would be great profit in the development of an accelerated test which unmistakably correlates with life tests.

ENDURANCE TEST DATA

The endurance tests made on longitudinal specimens of steel by the methods outlined above, using necked test pieces, are summarized in Table II.

When the endurance results on longitudinal test pieces (that is, the figures in the table down to "Transverse Specimens") are plotted against Brinell hardness, or, as in Fig. 13, against tensile strength, it is seen that the results fall about the same curve as do those of Moore(**2**), McAdam(**9**) and a few results of Aitchison(**30,31**), all these latter tests being in rotary bending with completely reversed stress. It will be noted that the endurance limits given were determined by tests carried to approximately one million cycles unbroken and checked up by running further at higher stresses. We believe that the good agreement between the results obtained by this method and those of other investigators indicates the value of this short-cut method in endurance testing on wrought steels.

S-LOG *N* CURVES FOR HARD STEELS

It will be noted that a few very strong steels of over 225,000 lb. per sq. in., that is, of practically "spring temper," have been tested, and that those do not show as high a ratio of endurance limit to tensile strength as is the case with softer steels.

TABLE II.—CHEMICAL AND MECHANICAL PROPERTIES AND THERMAL HISTORY OF THE STEELS TESTED.

Steel No.	Draw No.	Chemical Composition, per cent								Heat Treatment[1]					Tension Tests						Stanton Impact Test,[6] number of blows	Izod Impact Test,[7] ft-lb.	Brinell Hardness				Endurance Limit in Reversed Bending,[8] lb. per sq. in.
		C	Si	Mn	Ni	Cr	Mo	V	Ce	Quenched from			Temperature of Draw		Proportional Limit,[2] lb. per sq. in.	Yield Point by Extensometer,[3] lb. per sq. in.	Yield Point by Drop of Beam,[4] lb. per sq. in.	Tensile Strength,[5] lb. per sq in.	Elongation in 2 in., per cent	Reduction of Area, per cent			On Tension Specimens	On Stanton Specimens	On Izod Specimens	On Endurance Specimens	
										deg. Cent.	deg. Fahr.	Medium	deg. Cent.	deg. Fahr.													
1	3	0.40	0.29	0.77	...	...	...	...	...	870	1600	water	420	790	s	135 000	......	171 500	12.5	40.5	6300	31.5	375	350	350	325	68 000
	4									"	"	"	425	800	......	......	......	......	...	...	....	...	...	...	...	340	78 000
3	2	0.38	0.35	0.71	...	...	0.37	...	...	870	1600	water	360	680	s	185 000	......	207 500	12	49	6850	15.5	420	385	400	380	96 000
	3									"	"	"	420	790	s	170 000	......	187 500	13.5	52	6890	26	375	340	360	360	85 000
	N									840	1545	air	(normalized)		60 000	65 500	65 500	104 000	25	54.5	1480	27	210	205	190	180	50 000
2	3	0.41	0.42	0.72	...	...	0.67	...	...	870	1600	water	420	790	s	185 000	......	198 500	13.5	52	6430	22.5	390	390	390	420	91 000
	4									"	"	"	500	930	s	160 000	......	178 000	14.5	54.5	5800	28	370	340	360	370	92 000
	N									840	1545	air	(normalized)		67 500	71 000	......	119 000	21	51.5	2170	14	230	230	230	225	54 000
5	2	0.38	0.35	0.68	...	...	...	...	0.41 to 0.61[a]	870	1600	water	360	680	s	165 000	......	182 500	11.5	46	7030	41.5	360	360	360	365	80 000
	3									"	"	"	420	790	s	135 000	......	154 500	15.5	54.5	5435	52	310	310	310	300	70 000
55	1	0.50	0.16	0.84	...	...	..	0.20	...	840	1545	oil	475	885	148 000	155 000	156 000	171 500	15.5	55	4610	44.5	335	375	365	360	80 000
	2									"	"	"	555	1030	140 000	142 000	144 000	147 000	17	54	3340	58.5	305	320	320	310	75 000
	N									900	1650	air	(normalized)		95 000	96 000	97 000	125 000	25	54	1980	19	260	270	230	250	65 000
6	2	0.44	0.30	1.05	...	...	...	...	...	875	1610	oil	400	750	s	150 000	......	187 000	8.5	24	7600	15	380	385	385	385	89 000
	3									"	"	"	450	890	s	135 000	......	168 500	11	34	6790	17	330	350	350	375	85 000
8	2	0.44	0.33	1.29	...	...	0.34	...	..	875	1610	oil	450	890	s	170 000	......	194 500	11.5	37	7890	15	400	390	390	385	98 000
7	2	0.43	0.46	1.24	...	...	0.73	...	..	875	1610	oil	475	885	s	160 000	......	193 000	14.5	52	7200	20.5	395	390	390	385	96 000
	3									"	"	"	550	1020	s	157 000	......	181 500	17	49	5800	32	370	370	370	370	85 000
41	1	0.46	0.43	0.75	...	...	1.05	...	...	900	1650	oil	425	800	s	190 000	......	219 000	11.5	43.5	8050	29.5	420	420	420	430	98 000
	2									"	"	"	500	930	s	185 000	......	201 500	13.5	46	8840	36	405	390	390	385	96 000
	3									"	"	"	600	1110	s	180 000	......	194 500	16	49	6185	36	400	390	390	385	96 000
	N									"	"	air	(normalized)		s	75 000	......	140 000	17.5	43.5	1500	7	280	280	280	290	74 000
44	1	0.36	0.36	0.65	..	..	3.00	.	..	900	1650	oil	425	800	s	200 000	200 000	217 500	10.5	39.5	8770	12.5	430	420	425	420	104 000
	2									"	"	"	500	930	s	190 000	195 000	198 000	13.5	42	7300	20	415	420	415	420	108 000
	3									"	"	"	575	1065	s	166 000	167 000	176 500	14.5	47	....	...	355	...	...	370	115 000
9	1	0.35	0.35	0.62	..	0.94	..	...	...	900	1650	oil	425	800	s	160 000	......	194 500	12	40.5	8250	23	415	400	400	385	78 000±
	2									"	"	"	525	975	s	131 000	......	158 000	16.5	54.5	5340	55	340	325	310	320	80 000
	3									"	"	"	625	1150	s	105 000	110 000	126 500	22.5	64.5	3300	90	270	260	260	255	57 000

45	1	0.40	0.12	0.65	.	0.88	0.30	...	...	820	1510	oil	425	800	s	170 000	......	202 500	12	47.5	9370	8	420	445	445	420	98 000
	2									··	··	··	525	975	s	143 000		166 000	15	53	6475	26	330	385	375	360	87 000
	3									··	·	··	625	1150	s	111 500	118 000	133 500	21	65.5ᵃ	4225	58	290	320	300	300	70 000
11	2	0.41	0.28	0.63	...	0.89	0.36	...	...	900	1650	oil	525	975	s	155 000	......	178 000	14.5	52	5600	33.5	375	370	370	365	85 000
	N									840	1545	air	(normalized)		47 500	57 500	......	129 500	16.5	44	2445	12	250	245	245	240	65 000
10	1	0.40	0 40	0.62	...	0.95	0.68	..	...	900	1650	oil	425	800	s	170 000	......	219 000	12	43.5	8600	19	425	420	420	400	97 000
	2									··	··	··	525	995	s	165 000	......	203 500	13	46	6740	33.5	390	390	390	385	85 000±
	3									··	··	··	625	1150	s	145 000	......	174 000	15	52	6300	43	350	345	345	340	89 000
	N									820	1510	air	(normalized)		25 000	38 500	......	148 500	15	20	1640	6	285	300	275	255	67 000
12	1	0.40	0.31	0.64	...	0.93	...	0.20	...	900	1650	oil	425	800	s	160 000	......	193 000	11.5	49	8675	21	400	410	410	420	98 000
	2									··	··	··	525	975	s	152 500	156 500	164 500	16.5	54.5	5730	42	360	350	350	340	79 000
	3									··	··	··	625	1150	s	130 000	137 500	145 500	18	58	3825	57	305	280	280	255	62 000
57	1	0.41	0.13	0.67	...	0.93	...	0.16	...	900	1650	oil	425	800	175 000	190 000	......	208 500	13	46.5	...	...	400	...	...	420	88 000
	2									··	··	··	525	975	165 000	167 500	172 500	183 500	14	46.5	....	...	350	...	...	350	74 000
	3									··	··	··	625	1150	137 500	142 500	144 000	154 500	17	52	....	...	300	..	.	285	74 000
	N									··	··	air	(normalized)		85 000	91 000	94 500	126 000	22.5	62.5	2360	36	235	240	245	225	66 000
14	1	0.41	0.27	0.64	...	0.98	...	.	0.41 to 0.50ᵃ	900	1650	oil	425	800	s	185 000	......	217 500	9	30.5	5200	12.5	445	430	430	410	84 000
	2									··	··	··	525	975	s	130 000	......	149 500	17	54.5	4150	40	325	320	320	310	72 000
	3									··	··	··	625	1150	s	90 000	100 000	119 500	22	60	2770	52	245	240	240	240	59 000
47	1	0.15	0.12	0.36	...	0.73	0.28	...	...	925	1690	water	425	800	s	125 000	135 000	155 500	14	55.5	5400	53	320	300	320	310	61 000±
	2									··	··	··	525	975	s	105 000	115 000	126 000	18.5	64	4240	79	285	280	270	275	69 000
	3									··	··	··	625	1150	s	77 500	80 000	97 000	25.5	78.5	1840	117	215	195	185	200	52 000
46	1	0.22	0.14	0.59	...	0.79	0.34	...	...	850	1560	water	425	800	s	......	124 000	137 000	13.5	52	5820	32	330	365	340	345	80 000
	2									··	··	··	525	975	107 500	110 000	126 000	135 500	18	63	3840	56	320	300	300	310	75 000
	3									··	··	··	625	1150	s	90 000	104 500	116 000	22.5	69	3090	81	260	260	240	235	57 000
49	1	0.25	0.19	0.48	...	0.95	0.73	...	...	925	1690	oil	425	800	s	150 000	......	187 500	15	56.5	8160	33	400	385	385	375	86 000
	2									··	··	··	525	975	147 500	155 000	......	175 000	19	57.5	6450	59	385	365	365	345	81 000
	3									··	··	··	600	1100	126 000	131 000	140 000	150 000	20	66	....	...	320	...	...	300	72 000
48	1	0.42	0.19	0.55	...	0.55	0.39	...	...	925	1690	oil	425	800	......	187 500	......	207 000	14	51.5	6660	21	420	400	430	375	95 000
	2									··	··	··	525	975	......	162 500	......	175 000	17	55.5	6820	51	365	360	350	365	92 000
	3									··	··	··	630	1165	......	122 500	125 000	130 000	20	64.5	2975	95	255	280	250	300	79 000
50	1	0.52	0.16	0.71	..	0.95	0.39	...	...	815	1500	oil	425	800	s	170 000	......	209 000	13	48	7200	16	400	420	420	445	100 000
	2									··	··	··	525	925	s	155 000	159 000	188 000	17.5	51	6510	19	365	365	365	380	92 000±
	3									··	··	··	625	1150	s	100 000	105 500	135 000	19.5	55.5	3900	72	285	310	285	255	60 000
15	2	0.47	0.36	0.64	1.23	0.65	..	....	...	825	1515	oil	525	975	s	145 000	147 000	159 500	15.5	54.5	5270	47	345	330	330	320	83 000
17	2	0.39	0.27	0.66	1.28	0.68	0.31	...	...	825	1515	oil	525	975	s	155 000	160 000	168 500	15	54.5	5870	37	355	350	350	340	88 000
16	1	0.41	0.41	0.64	1.27	0.67	0.83	..	...	825	1515	oil	425	800	s	180 000	196 500	224 000	12.5	46	7250	16	460	460	460	440	100 000
	3									··	··	··	625	1150	s	165 000	171 500	182 500	14 5	52	5920	34	380	370	370	365	74 000
18	2	0.39	0.28	0.71	1.20	0.74	...	0.24	...	825	1515	oil	525	975	s	150 000	156 000	160 000	13	54.5	6085	44	340	330	330	320	88 000
20	2	0.41	0.33	0.63	1.17	0.77	..		0.25	825	1515	oil	525	975	s	130 000	134 000	149 000	17	54 5	4120	43	310	305	305	300	82 000

NOTE.—For references, see p. 504.

TABLE II.—CHEMICAL AND MECHANICAL PROPERTIES AND THERMAL HISTORY OF THE STEELS TESTED (*Continued*).

Steel No.	Draw No.	Chemical Composition, per cent								Heat Treatment[1]					Tension Tests						Stanton Impact Test,[6] number of blows	Izod Impact Test,[7] ft-lb.	Brinell Hardness				Endurance Limit in Reversed Bending,[8] lb. per sq. in.
		C	Si	Mn	Ni	Cr	Mo	V	Ce	Quenched from			Temperature of Draw		Proportional Limit,[2] lb. per sq. in.	Yield Point by Extensometer,[3] lb. per sq. in.	Yield Point by Drop of Beam,[4] lb. per sq. in.	Tensile Strength,[5] lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent			On Tension Specimens	On Stanton Specimens	On Izod Specimens	On Endurance Specimens	
										deg. Cent.	deg. Fahr.	Medium	deg. Cent.	deg. Fahr.													
52	1	0.54	0.48	0.84	1.02	0.84	...	...	0.12	810	1490	oil	420	290	[8]	195 000	200 000	214 000	9	27.5	4920	13	440	450	435	420	97 000
	2									"	"	"	525	975	[8]	145 000	149 500	161 500	16	46	3345	31	345	330	330	315	75 000
21	2	0.36	0.33	0.65	2.56	0.83	...	...	...	810	1490	oil	525	975	[8]	140 000	144 500	151 500	17	57.5	4720	47.5	310	305	305	300	68 000
										"	"	"	625	1150	[8]	115 000	119 500	126 000	24	64.5	3015	74	260	255	255	250	65 000
23	3	0.46	0.32	0.61	2.45	0.88	0.35	...	...	810	1490	oil	625	1150	[8]	140 000	144 500	157 500	19	60	5015	54	325	320	320	310	80 000
22	A	0.41	0.31	0.60	2.49	0.79	0.76	...	...	810	1490	oil	150	300	170 000	187 500	......	312 000	11	29.5	....	...	520	...	...	530	135 000±?
	X									"	"	"	225	435	......	......	......	......	...	...	....	22	...	...	530	475	125 000±?
	C									805	1480	"	325	615	197 000	200 500	......	246 000	11.5	40	....	...	475	...	...	445	100 000±?
	1									810	1490	"	425	800	[8]	175 000	180 000	220 000	12	40.5	6800	16	445	425	425	425	96 000
	2									"	"	"	525	975	[8]	165 500	170 000	204 000	11.5	45	5040	23	410	405	405	400	100 000
	3									"	"	"	625	1150	[8]	145 000	150 500	169 000	16.5	54.5	4635	32	340	330	330	310	83 000
	5									"	"	"	650	1200	140 000	146 500	146 500	157 500	18	55	....	...	320	...	...	275	72 000
26	1	0.50	0.44	0.63	2.39	0.86	0.75	...	...	790	1450	oil	430	805	[8]	207 000	213 000	238 000	10	34	4880	15	465	460	460	445	102 000
	2									"	"	"	525	975	[8]	190 000	193 500	210 000	11.5	37	4850	18	425	430	425	420	87 000
	3									"	"	"	630	1165	[8]	150 000	154 500	164 000	16	49	5540	34	335	350	340	320	70 000
24	1	0.40	0.28	0.61	2.52	0.84	...	0.20	...	810	1490	oil	425	800	[8]	187 500	200 000	207 500	12.5	52	8560	35	405	415	390	420	100 000
	3									"	"	"	625	1150	[8]	140 000	150 000	152 000	17	54.5	4540	50	320	300	300	285	75 000
25	2	0.43	0.35	0.58	2.47	0.95	...	...	0.24	810	1490	oil	525	975	137 500	142 500	143 000	153 500	17	52	4150	31	320	330	340	320	77 000
I-9[e]	C	0.41	2.47	0.70	3.00	...	...	...	...	860	1575	oil	415	775	211 500	......	......	254 000	8	31.5	....	21.5	505	...	505	505	110 000±
	D									"	"	"	510	950	170 000	......	......	192 500	11	26	....	6	410	...	410	410	90 000
	A									"	"	"	595	1100	145 500	......	......	169 500	14	26.5	....	12	360	...	360	360	85 000
	B									"	"	"	595	1100	148 000	......	......	164 500	14	28	....	17	345	...	345	345	88 000
I-10[b]	D	0.40	2.73	0.57	2.95	...	...	...	...	860	1575	oil	400	750	226 500	......	......	269 500	8	32	....	25.5	520	...	520	520	110 000
	C									"	"	"	540	1000	167 000	......	......	185 000	11.5	21	....	14.5	385	...	385	385	85 000
	B									"	"	"	595	1100	150 500	......	......	176 500	15	37	....	12	355	...	355	355	94 000
	A									"	"	"	595	1100	131 000	......	......	156 000	18	34	....	17	320	...	320	320	85 000
I-16[c]	B	0.43	2.40	0.57	3.00	...	...	...	0.24 Zr	860	1575	oil	370	700	219 500	......	......	281 500	7.5	31.5	....	22.5	510	...	510	510	109 000

I-32	C	0.43	2.54	0.91	2.86	...	...	...	0.58 to 0.32[a]	860	1575	oil	425	800	200 000	......	......	242 000	1.5	4	....	17.5	510	...	510	510	96 000±
	D									"	"	"	455	850	149 000	......	......	199 000	8	10	....	8	405	...	405	405	83 000
	B									"	"	"	595	1100	142 000	......	......	167 000	11	24	....	16	350	...	350	350	76 000
	A									"	"	"	595	1100	137 000	......	......	160 500	6.5	10	....	22.5	330	...	330	330	72 000±
I-28	A	0.36	2.42	0.51	2.94	...	...	0.12	...	870	1600	oil	400	750	224 000	......	......	262 500	7	19.5	....	22	520	...	520	520	100 000
	B									"	"	"	510	950	181 000	......	......	206 000	9	21	....	14	425	...	425	425	105 000
	C									"	"	"	610	1125	158 000	......	......	184 000	11.5	25.5	....	13	390	...	390	390	96 000
I-30	C	0.37	2.50	0.52	2.95	...	0.70	...	...	860	1570	oil	595	1100	163 500	......	......	185 500	7	29	....	17.5	385	...	385	385	92 000
	B									"	"	"	620	1150	145 500	......	......	176 000	12	28	....	8.5	340	...	340	340	92 000
	A									"	"	"	620	1150	146 500	......	......	171 000	15	37	....	26	340	...	340	340	92 000
LONGITUDINAL AND TRANSVERSE SPECIMENS, ALSO REDRAWN SPECIMENS																											
32[f]	L LR	0.37	0.28	0.63	2.49	0.83	...	...	...	805	1480	oil	475 Redrawn	885	150 000	155 000	158 500	168 500	15.5	53	5760	25[h]	350	350	350	350 320	85 000 88 000
	T									"	"	"	475	885	147 500	152 500	157 500	168 000 157 000	10 1	33.5 5	3890	12	340	340	340	345	70 000±
34[f]	L LR	0.44	0.43	0.66	2.44	0.82	0.37	...	...	805	1480	oil	625 Redrawn	1150	132 500	137 500	141 000	161 000	18.5	52	4340	31.5	340	340	340	320 295	69 000 83 000
	T TR									"	"	"	625 Redrawn	1150	132 000	136 000	143 000	161 000	15	37.5	3640	12.5	340	340	340	320 300	65 000 78 000±
37[f]	L LR	0.53	0.36	0.65	2.52	0.83	0.34	...	...	790	1450	oil	610 Redrawn	1130	135 000	141 000	146 000	166 500	17	45	4550	27	345	345	340	330 300	67 000 88 000
	T TR									"	"	"	610 Redrawn	1130	135 000	139 000	145 000	165 500	9 11.5	15.5 22.5	2980	11	345	350	350	310 300	58 000 70 000
33[f]	L LR	0.38	0.48	0.61	2.53	0.78	0.75	...	...	790	1450	oil	635 Redrawn	1175	139 000	145 000	152 500	164 000	18.5	52.5	5360	26.5	340	350	340	335 300	72 000± 84 000
	T TR									"	"	"	635 Redrawn	1175	132 500	137 500	152 000	164 000	12.5	34	3510	11	340	350	340	340 295	56 000 71 000
35[f]	L LR	0.41	0.34	0.58	2.52	0.85	...	0.19	...	805	1480	oil	560 Redrawn	1040	151 000	156 000	160 500	161 000	16	48.5	4185	26	340	340	340	320 300	71 000 81 000 89 000
	T TR									"	"	"	560 Redrawn	1040	150 000	155 000	160 000	162 500	11.5	26	3040	11	340	340	340	320 300	60 000± 75 000± 80 000
36[f]	L	0.36	0.34	0.66	2.46	0.92	...	...	0.19	805	1480	oil	500	930	139 500 132 500	145 000 137 000	146 500	159 000	14.5	34.5 45	4290	29	330	330	330	340	80 000
	T									"	"	"	"	"	131 750	135 000	140 000	140 000 150 500	4 2	10 8.5	3875	17	320	330	330	330	69 000± (or 60 000 to 75 000)

NOTE.—For references, see p. 504.

TABLE II.—CHEMICAL AND MECHANICAL PROPERTIES AND THERMAL HISTORY OF THE STEELS TESTED (*Continued*).

Steel No.	Draw No.	Chemical Composition, per cent								Heat Treatment[1]					Tension Tests						Stanton Impact Test,[6] number of blows	Izod Impact Test,[7] ft-lb.	Brinell Hardness				Endurance Limit in Reversed Bending,[8] lb. per sq. in.
		C	Si	Mn	Ni	Cr	Mo	V	Ce	Quenched from			Temperature of Draw		Proportional Limit,[2] lb per sq. in.	Yield Point by Extensometer,[3] lb. per sq. in.	Yield Point by Drop of Beam,[4] lb. per sq. in.	Tensile Strength,[5] lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent			On Tension Specimens	On Stanton Specimens	On Izod Specimens	On Endurance Specimens	
										deg. Cent.	deg. Fahr.	Medium	deg. Cent.	deg. Fahr.													
TRANSVERSE SPECIMENS																											
I-9	CT	0.41	2.47	0.70	3.00	...	...	...	...	860	1575	oil	415	775	224 500	......	......	246 000	1	4.5	....	19	505	...	505	505	95 000±
	DT									"	"	"	510	950	169 500	......	......	192 000	10	20	....	7	410	..	410	410	94 000
	AT									"	"	"	595	1100	152 000	......	......	173 000	14.5	29	....	7.5	360	...	360	360	82 000
	BT									"	"	"	595	1100	147 500	......	......	158 000	5	7	....	17	345	...	345	345	82 000
I-10	DT	0.40	2.73	0.57	2.95	...	...	...	...	860	1575	oil	400	750	218 000	......	......	268 000	5	6.5	....	17	520	...	520	520	100 000
	CT									"	"	"	540	1000	161 000	......	......	182 000	10	13	....	10	385	...	385	385	85 000±
	BT									"	"	"	595	1100	136 000	......	......	163 500	11.5	15	....	17.5	355	...	355	355	87 000
	AT									"	"	"	595	1100	139 500	......	......	161 500	17	34	....	18.5	320	...	320	320	87 000
I-16[c]	BT	0.43	2.40	0.57	3.00	...	...	...	0.24 Zr	860	1575	oil	370	700	224 000	......	......	284 500	4	10	...	10	510	...	510	510	100 000 or less[d]
I-30	DT	0.37	2.50	0.52	2.95	...	0.70	...	...	860	1575	oil	400	750	228 500	......	......	272 500	6	22	....	15	515	...	515	515	100 000±
I-32	CT	0.43	2.54	0.91	2.86	...	...	...	0.58 to 0.33[a]	860	1575	oil	425	800	212 500	......	......	255 000	6	20.5	...	11.5	510	...	510	510	94 000±
	DT									"	"	"	455	850	158 000	......	......	185 000	2.5	4.5	....	10.5	405	...	405	405	75 000
	BT									"	"	"	595	1100	142 000	......	......	169 000	11.5	12.5	....	16	350	...	350	350	74 000±
	AT									"	"	"	595	1100	130 500	......	......	156 000	6	7.5	...	10	330	...	330	330	72 000±

[a] In the steels containing over 0.25 per cent cerium, there was segregation of Ce, the amount of Ce in the top of the ingot being larger than that in the bottom. "Ce" includes the other metals of the Ce group.

[b] Steel I-10 also contained 0.03 per cent zirconium.

[c] Steel I-16 also contained 0.24 per cent zirconium.

[d] Most of the transverse endurance specimens of I-16 broke at the upper jaw, not at the neck.

[e] "I" steels rolled to $\frac{1}{4}$ in. thick by 12 in. wide from 3 by 6-in. ingot. First spread to 12 in. by cross-rolling, then finished lengthwise.

[f] Steels Nos. 32 to 37 were rolled to 0.6 in. thick by 6 in. wide from a 3 by 6-in. ingot without any cross-rolling at all.

[g] Steels Nos. 32 to 37 furnace cooled after the draw on the regular tests. All others air-cooled from the draw.

[h] Regular round full size Izod specimen on steels Nos. 32 to 37.

[1] All specimens treated in small sizes, $\frac{3}{4}$ in. or less. Usually treated in $\frac{1}{16}$-in. oversize and ground to size. "I" steels heat-treated in 12 by 12 by $\frac{1}{4}$ in. and specimens cut from the plates by thin abrasive wheel. Single heat treatment used. All draws at temperature 1 hour, except on "redraws" and on some of the "I" specimens, which had longer draws.

[2] Proportional limit taken from stress-strain diagram with Berry gage on 2-in. test length, where given. When letter *s* appears, tests were made with a "scissors" extensometer not sufficiently accurate to show proportional limit.

[3] Extensometer yield point is the first deviation from straightness of the stress-strain curve with the "scissors" extensometer. When the Berry gage was used, the point found by taking an offset from the straight line equal to 0.0002 in. per inch inelastic extension is given, as this corresponds with the first detectable deviation with the "scissors" instrument.

[4] Yield point by drop of beam, where noted, shows the stress at which the load balanced after stopping the machine as soon as the drop occurred, not the slightly higher figure at the instant of drop.

[5] Tension test specimens (except for flat "I" steels) 0.505 in. diameter breaking section by 2-in. gage length, held in ball and socket holders. Specimens on "I" steels flat, $\frac{1}{4}$ by $\frac{1}{2}$ in. by 2-in. gage length, held in wedge grips. 100,000-lb. 3-screw Olsen machine used, pulling at 0.04 to 0.025 in. per minute. Tension tests on "I" steels made by Navy Department.

[6] Stanton tests made by Wyman-Gordon Co. Specimen 0.500 in. in diameter, 4.500-in. span between supports. Notch flat bottomed, 0.05 in. wide by 0.05 in. deep. Hammer about 5 lb.; height of fall 2 in.; speed, 100 blows per minute. Figures are average of 2 or more tests.

[7] Izod tests made by Wyman-Gordon Co. Specimen round, 0.450-in. diameter with Izod V notch, 45 deg., 0.01-in. (except for flat "I" steels) radius at base of notch (sharp notch). 120-ft-lb. machine used. Figures are average of 4 tests Izod specimens on "I" steels 0.25 by 0.394 by 4-in. notch, 0.079 in. deep, 0.039 in. radius (Mesnager notch). Results given are calculated over to the basis of a specimen 0.394 by 0.394 in. Figures are average of 2 tests.

[8] Endurance specimens (except on flat "I" steels) round, necked piece; on "I" steels, flat necked piece. Upton-Lewis machines used. Stress completely reversed. Figure given is the equal tensile and compressive stress, that is, half the stress range.

On the basis of tests on steels of up to say 200,000 lb. per sq. in. tensile strength, Moore, McAdam, and various English workers have pointed out that the endurance limit in rotary bending with completely reversed stress, generally runs from 45 to 55 per cent of the static tensile strength, averaging very close to 50 per cent. That is, the endurance stress range is equal to the tensile strength. Moore(2) draws the curve of endurance limit vs. tensile strength or Brinell hardness as a straight line up to 280,000 lb. per sq. in. tensile strength or 560 Brinell. Moore made two tests on his steel No. 7 (3.5 per cent nickel), oil-quenched, no draw, 520 Brinell, 294,000 lb. per sq. in. tensile strength and 112,000 lb. per sq. in. endurance limit) on which the endurance limits were approximated from tests of a smaller number of specimens than usual. The results were less consistent than usual, several breaking at the grip. The endurance figures are also to be considered less significant. If these points be considered in his plots, it is obvious that the curve is not a straight line at the high tensile-strength end, especially if the several points at about 240,000 lb. per sq. in. tensile strength (105,000 lb. per sq. in. endurance limit) are given weight. Aitchison(30) gives the properties shown in Table III for a steel of 0.30 per cent carbon, 0.56 per cent molybdenum, 4.30 per cent nickel and 1.44 per cent chromium, air-hardened from 800° C. (1470° F.):

TABLE III.—PROPERTIES OF NICKEL-CHROME-MOLYBDENUM STEEL.

C, 0.30; Mo, 0.56; Ni, 4.30; Cr, 1.44. Air-hardened from 800° C. (1470° F.)

Temperature of Draw		Proportional Limit, lb. per sq. in.	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Endurance Limit, lb. per sq. in.
deg. Cent.	deg. Fahr.						
none	none	45 000	176 000	244 000	11	36.5	102 000
200	390	81 000	173 000	227 000	12.5	41.5	115 000
400	750	119 000	179 000	220 000	10	36	106 000
500	930	105 000	159 000	185 000	15	46.5	93 000
600	1110	91 500	141 000	157 000	17.5	55	79 500

Hatfield(33,34) has given the following figures for an air-hardened (820° C., 1510° F.) untempered steel of 0.30 per cent carbon, 0.40 per cent manganese, 4.07 per cent nickel and 1.38 per cent chromium:

Tensile Strength, lb. per sq. in.	245 000
Yield Point, lb. per sq. in.	121 000
Elongation, per cent	9
Reduction of Area, per cent	21
Endurance Limit, lb. per sq. in.	71 500

Whyte(35) finds a similar endurance limit for a similar untempered steel, and states that the endurance limit rises until a draw temperature of 400° C. (750° F.) is passed, when it starts to fall. It is not certain that Hatfield's or Whyte's endurance specimens had the proper form of neck or fillet and some of Hatfield's endurance figures for other steels seem a bit low for the tensile strength shown. The figures are therefore perhaps only of qualitative value.

Moore(2) obtained the properties reported in Table IV on a 0.49-per-cent carbon steel quenched from 790° C. (1450° F.) in oil:

TABLE IV.—PROPERTIES OF A CARBON STEEL, ACCORDING TO MOORE.

$C = 0.49$. Quenched from 790° C. (1450° F.)

Temperature of Draw		Proportional Limit, lb. per sq. in.	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Endurance Limit, lb. per sq. in.
deg. Cent.	deg. Fahr.						
none	none	72 000	80 900	126 500	12.5	52	65 000
315	600	73 300	80 800	126 800	11.5	52	68 000
425	800	75 800	78 800	121 800	11.5	51	64 000

EFFECT OF INTERNAL STRESS ON ENDURANCE LIMIT

The endurance limit is thus raised by a tempering which does not lower the tensile strength, and even a tempering which perceptibly lowers (3.75 per cent) the tensile strength, scarcely (1.5 per cent) lowers the endurance limit.

It therefore appears that the internal stress introduced in hardening a steel by quenching (whether this be in water, in oil or in air, according to the rate of cooling required to harden the particular steel) may be a cause for the endurance limit being less than 50 per cent of the tensile strength. If this internal stress is not relieved by tempering, it may keep the endurance limit from being as high as would be expected from the tensile strength. Lessells(49) has noted this and suggests that the amount of internal stress is shown by the ratio of the elastic limit to the yield point, defining(50) elastic limit as the stress for the first deviation from a straight-line stress-strain relation and yield point as the stress for an extension of 0.01 in. on a 2-in. gage length. He suggests, too, that this ratio is a factor by which the endurance limit may be calculated from the tensile strength in steels of similar microstructure.

While this is a step in the right direction, other "stress raisers," for example, non-metallic inclusions, may simultaneously be exerting an effect which is not susceptible to quantitative measurement.

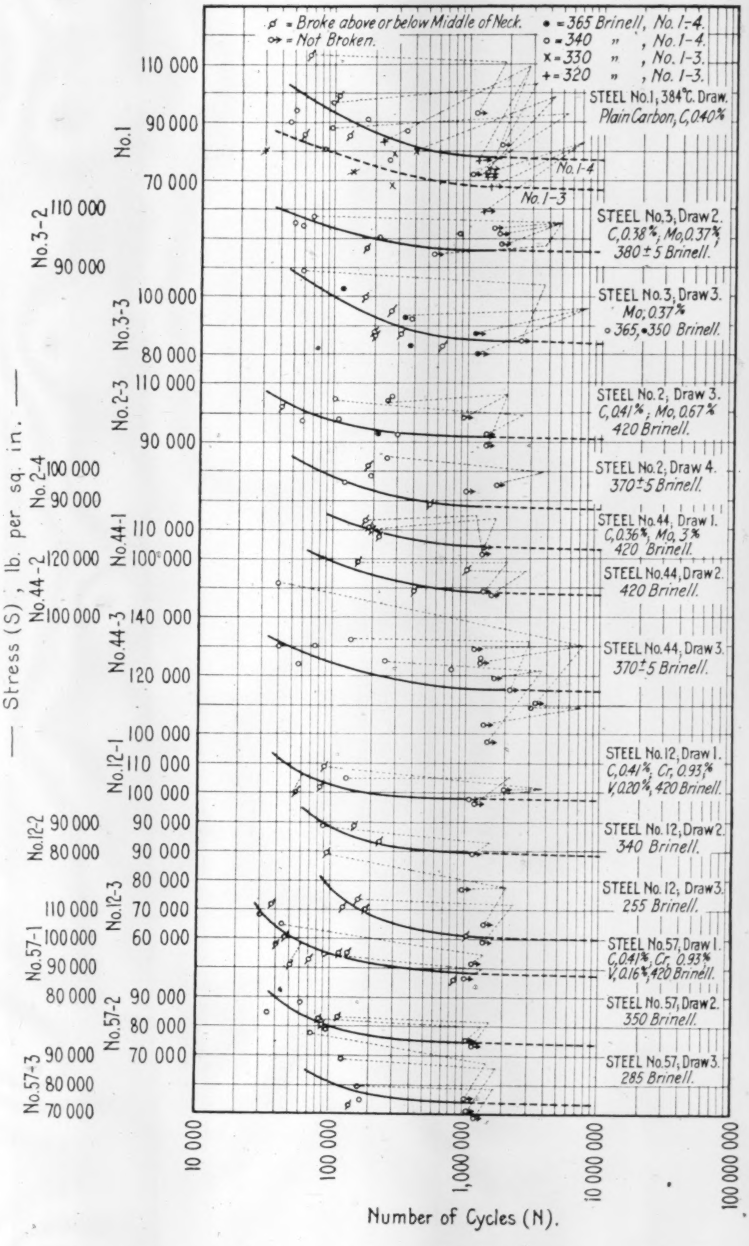


FIG. 9.—Upton-Lewis Endurance Tests of Necked Specimens of Steel.

Points connected by converging dotted lines indicate retesting of unbroken specimens at a higher stress.

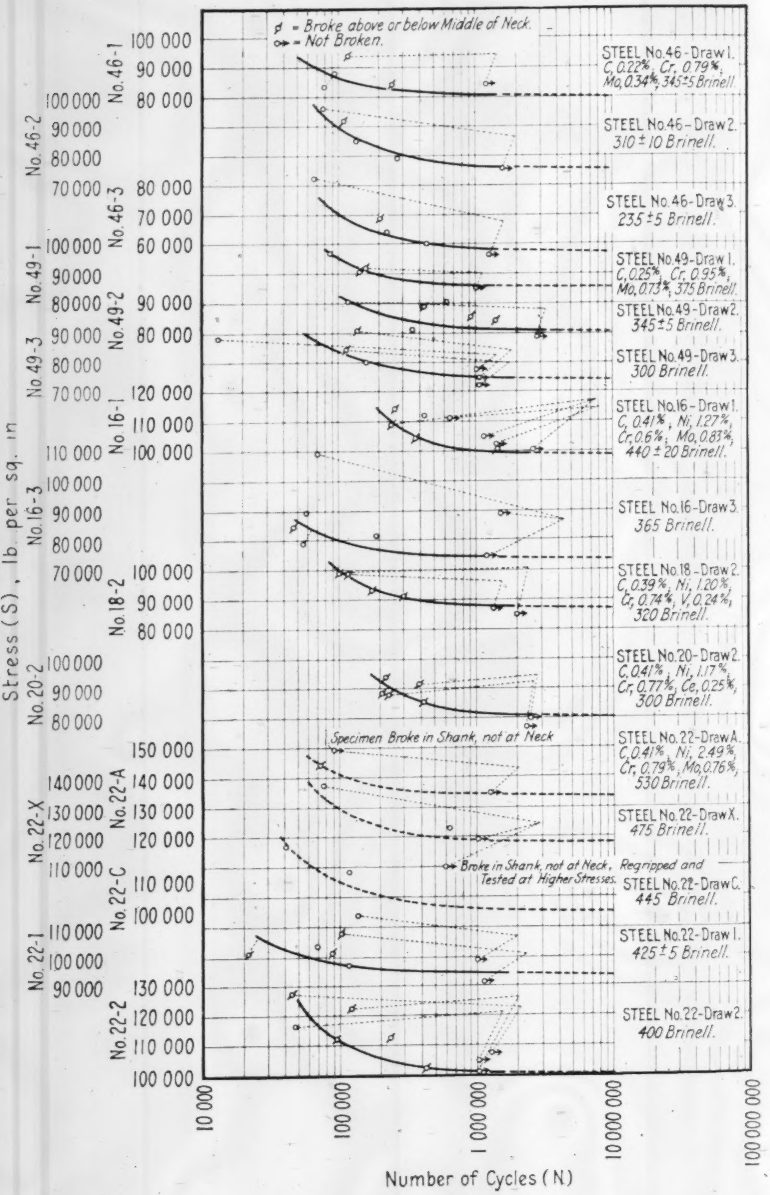


FIG. 10.—Upton-Lewis Endurance Tests of Necked Specimens of Steel.

Points connected by converging dotted lines indicate retesting of unbroken specimens at a higher stress

Longitudinal and transverse specimens differ but little in proportional limit, yield point, and tensile strength, and for this reason Lessells' formula would not indicate the difference that exists between the endurance limit of longitudinal and transverse specimens.

In Fig. 13 (*a*) has been drawn the average curve of Fig. 13, which is based on tests of necked round specimens, together with the results of a series of tests on necked flat specimens of nickel-silicon steels. Fig. 13 (*a*) shows even more plainly than Fig. 13 that the endurance limit – tensile strength plot is not a straight line. It also shows the lower endurance limit of a dirty steel such as the cerium steel, or with transverse specimens.

The tensile strength – endurance limit plot of Fig. 13 starts to curve at about 175,000 lb. tensile strength or 360 Brinell hardness or, what is more likely the real variable, a tempering temperature of about 400° C. (750° F.). This is also approximately the draw temperature for maximum specific gravity and maximum solubility of a hardened steel. It is even more likely that the temperature and time of the draw are the variables which should be considered in determining the slope of this portion of the curve. It is thought that this temperature may be approximated by noting the point at which the static proportional limit ceases to rise with increase of draw temperature and time. Aitchison has discussed this point at length and shows it coincides with the disapperance of martensite. But, as Plate I (*b*) shows, a martensitic structure need not cause the endurance limit to be much below the usual 50-per-cent ratio. On the other hand, if the steel is of such a composition that it can be drawn just past the martensite stage, say to a mixture of troostite and fine sorbite, at a temperature that will release the internal stress and is so resistant to tempering that the drawing can readily be stopped there and the sorbite kept from becoming too coarse, the endurance limit may be higher than the 50-per-cent ratio.

Plate I (*c*) shows the structure of a steel of 0.36 per cent carbon and 3 per cent molybdenum drawn at 575° C. (1065° F.). Molybdenum gives great resistance to tempering so that quenched steels containing molybdenum have to be drawn at very much higher temperature than do similar steels without molybdenum, in order to soften them to the same degree. This steel shows (see Table II and Fig. 9) at 425° C. (800° F.) an endurance limit just above the curve of Fig. 13, at 500° C. (930° F.), one 12,000 lb. per sq. in. above the curve, and at 575° C. (1065° F.), and one about 16,000 lb. per sq. in. above the curve.

Aitchison's air-hardening steel at the 200° C. (390° F.) draw also shows an endurance limit of 10,000 lb. per sq. in. above the curve

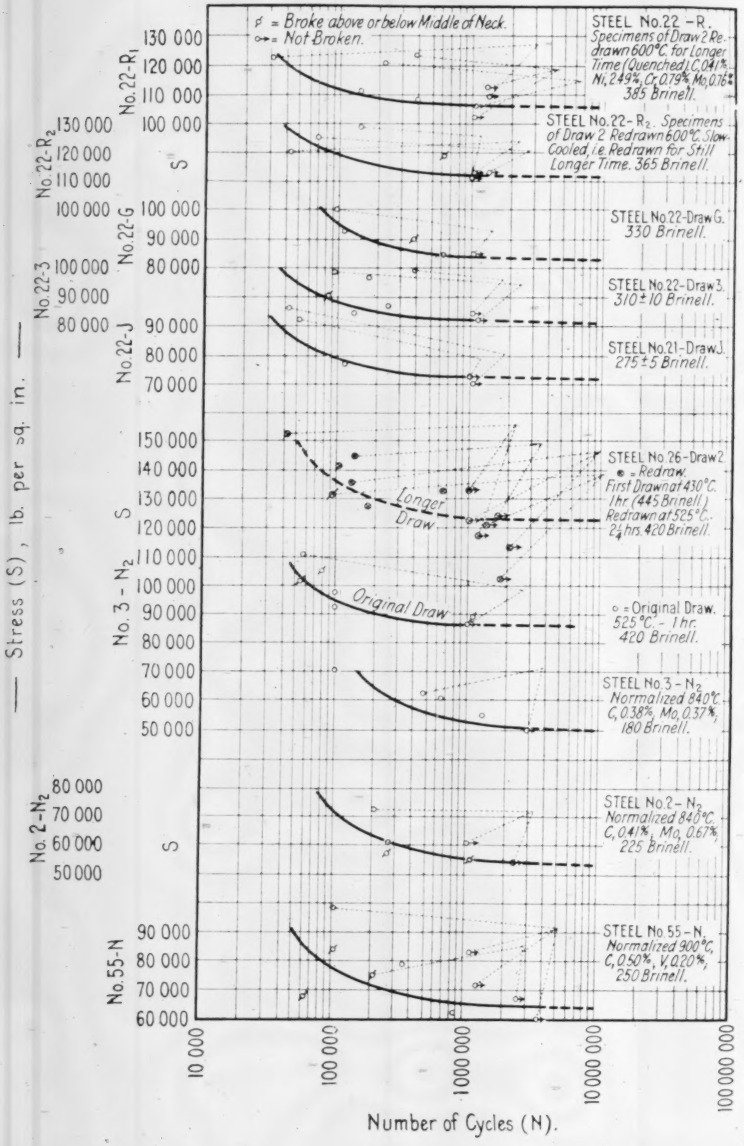


FIG. 11.—Upton-Lewis Endurance Tests of Necked Specimens of Steel.

Points connected by converging dotted lines indicate retesting of unbroken specimens at a higher stress.

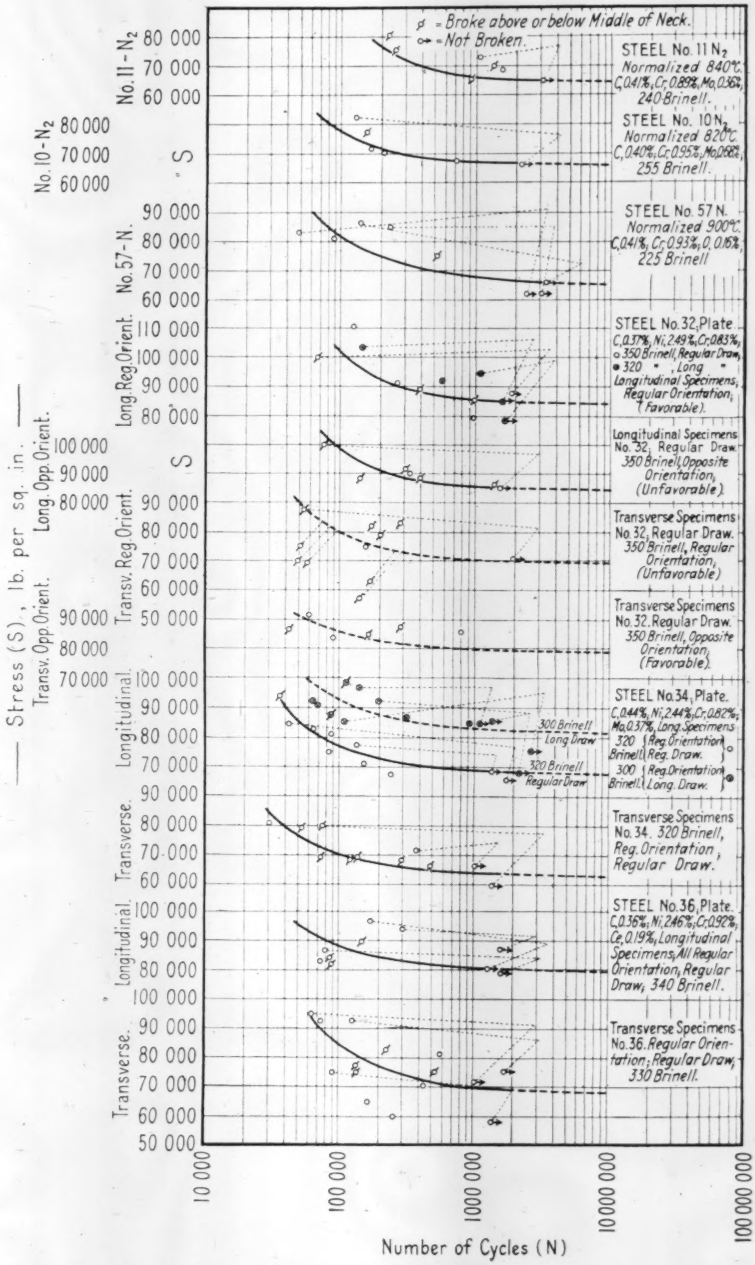


FIG. 12.—Upton-Lewis Endurance Tests of Necked Specimens of Steel.

Points connected by converging dotted lines indicate retesting of unbroken specimens at a higher stress.

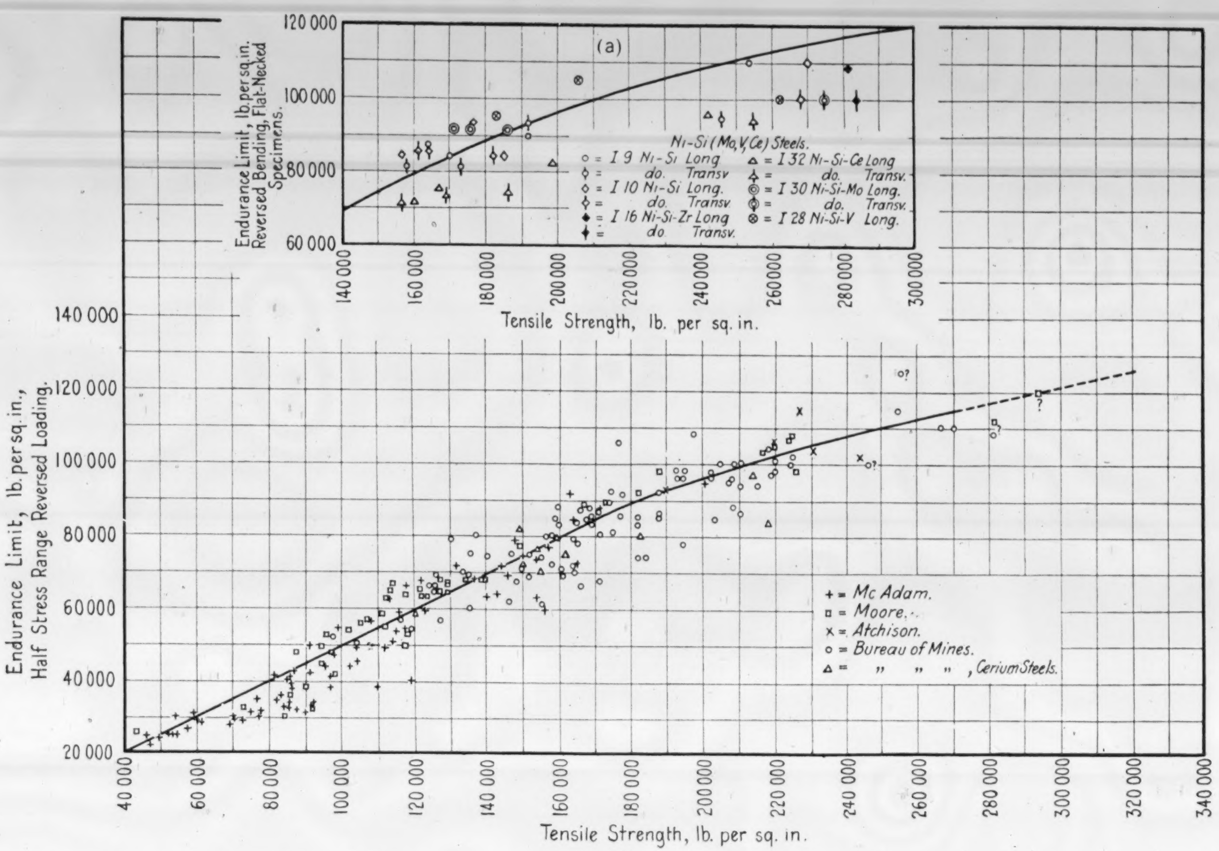


FIG. 13.—Endurance Limits Plotted Against Tensile Strengths. Endurance Limit Determined on Necked Round Specimens of Steel.

In Fig. (*a*), the points plotted represent endurance limit determined on necked flat specimens of nickel-silicon steels. The curve drawn is a portion of the average curve in the principal part of the figure.

(and on a prolongation of the straight line of the lower end of the curve), although his data show that the internal stress has not been fully relieved at that temperature. The endurance limit is probably the resultant of at least two factors, the tensile strength and the internal quenching stress. The latter is probably smaller in steels of lower carbon content, other things being equal.

Three other points, with question marks after them, are shown in Fig. 13, one of which is also on the prolongation of the straight-line curve. These are approximated from tests on only two specimens each from very low-temperature draws (150° C. (300° F.) and 225° C. (435° F.), 325° C. (615° F.)) of steel No. 22 (see Table II, Fig. 10). Internal stress was certainly present in the specimens at the lowest draw temperature, 150° C. (300° F.). These were necked down and polished two months after heat treatment. The usual examination for absence of circumferential scratches was made with a lens, and no cracks were present. Six months later, when they were again examined before testing, longitudinal cracks were found in both bars, extending along the shank just into the neck, the area of minimum section and most of the rest of the neck being uncracked. The specimens were placed in the endurance testing machine with the cracks on the neutral or unstressed axis, and the cracks did not develop farther during testing. After $1\frac{1}{4}$ million cycles at 135,000 lb. per sq. in., one specimen broke in the grip. On re-gripping and testing at 150,000 lb. per sq. in., the piece again broke in the grip after 90,000 cycles. The other specimen, tested at 145,000 lb. per sq. in., broke in the neck after 70,000 cycles, but above the point of minimum section. One specimen drawn at 225° C. (435° F.) also broke at the grip.

These sketchy tests are of no quantitative value, but are included for what they may indicate qualitatively. Any steel of over 240,000 lb. per sq. in. tensile strength, 480 Brinell, probably has very great unrelieved internal quenching stress and data on endurance of such steel should be interpreted with this fact in mind.

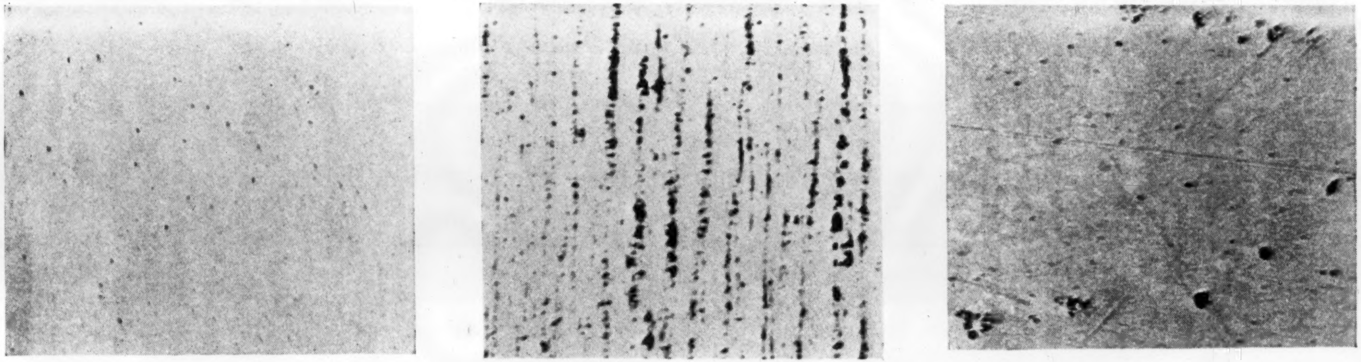
The effect of increasing the time or temperature of the draw was studied on some specimens of steel No. 22, draw 2, 525° C. (975° F.) and the results are shown in Fig. 11. At the original 1-hour draw at this temperature the steel had 204,000 lb. per sq. in. tensile strength, 400 Brinell, and 100,000 lb. per sq. in. endurance limit. Some of the specimens of this draw were put in a salt bath at 400° C. (750° F.) and the temperature raised to 600° C. (1110° F.) in $3\frac{1}{2}$ hours. Half were then taken out and the other half very slowly cooled in the salt bath to 100° C. (210° F.) in about 16 hours. The bath was then melted and the other half of the specimens taken out. This gave two lots, the first (*A*) of which was softened to 385 Brinell and the second (*B*) to 365 Brinell. The endurance limits were as follows:

	BRINELL	ENDURANCE LIMIT, LB. PER SQ. IN.
Original Lot	400	100 000
Re-draw *A*	385	106 000
Re-draw *B*	365	112 000

A similar test was made on steel No. 26, draw 2, 525° C. (975° F.) (1 hour) which showed 210,000 lb. per sq. in. tensile strength, 420 Brinell, and only 87,000 lb. per sq. in. endurance limit, that is, below the curve of Fig. 13. As no more draw 2 specimens were available, some specimens originally drawn 1 hour at 430° C. (805° F.), giving 238,000 lb. per sq. in. tensile strength, 445 Brinell, 102,000 lb. per sq. in. endurance limit were re-drawn $2\frac{1}{4}$ hours more at 525° C. (975° F.). The Brinell hardness was the same as on the 1-hour draw, 420, but the endurance limit was 123,000 lb. per sq. in. (Fig. 11). As Plates III (*a*) and (*b*) show, no visible difference in structure is produced by the longer tempering, as would be expected from the unchanged Brinell hardness figure.

The effect of increased tempering was also studied on some specimens (steels Nos. 32 to 37) from plates which were rolled entirely in one direction without cross-rolling, in which tests were made on specimens cut both longitudinally and transversely. These steels all contained about 2.50 per cent nickel, and 0.80 per cent chromium, and some of them contained molybdenum, vanadium or cerium. The steels were drawn for 1 hour at temperatures so chosen as to bring all specimens to about 340 Brinell, as shown at the end of Table II. But in this case, the steels that harden most readily on quenching and require the highest draw temperatures to soften, gave endurance limits below the value expected from the tensile strength. The transverse specimens gave results in all cases below those of the longitudinal ones. In so far as material was available, specimens were re-drawn for prolonged periods, and endurance tests then made.

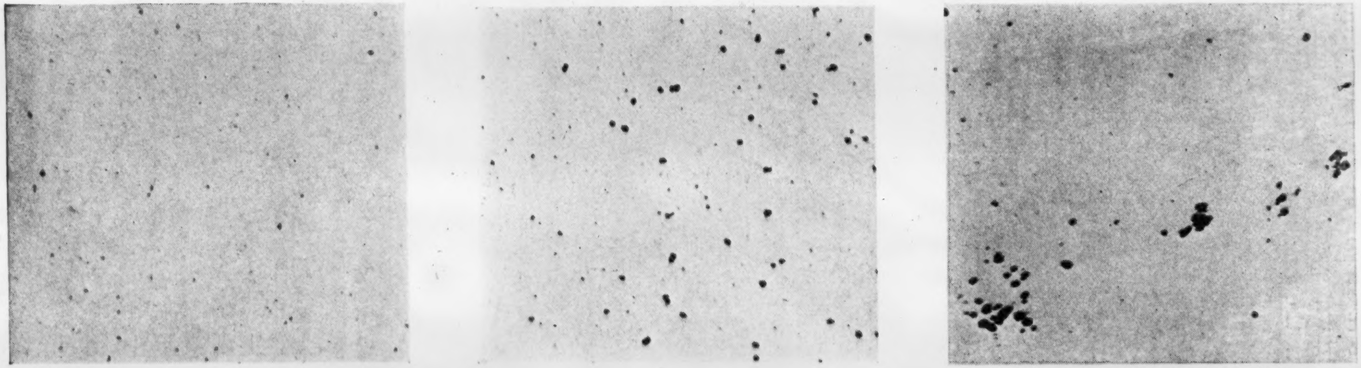
The data are reported in Table V. In Fig. 14 these data, as well as those on the redraws of steels Nos. 22 and 26, are plotted, the full line being the average curve of Fig. 13 and the broken lines showing the usual range of "scatter" above and below that curve. The endurance limit of a steel for the shortest draw time is plotted against the Brinell hardness and that point is connected by a line, bearing an arrow, with the point or points for the endurance limit after a longer draw or draws. The transverse specimens (whose points are denoted by an (×) still show lower endurance than the longitudinal ones,



(a) Specimen from rolled bar stock chrome-cerium steel.

(*b*) Specimen from rolled plate stock nickel-chrome-cerium steel. Section normal to direction of rolling, and from top of ingot just below pipe.

(*c*) Specimen from plain cerium steel.

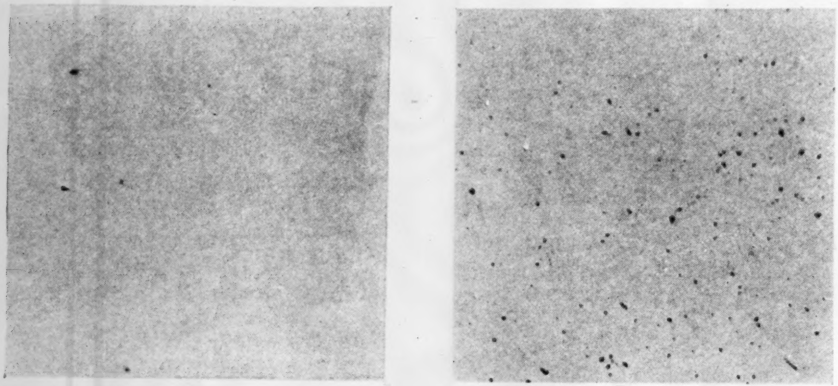


(*d*) (*e*) (*f*)

Micrographs (*a*), (*d*), (*e*), and (*f*) are of transverse sections through different specimens of the same hea tof chrome cerium steel.

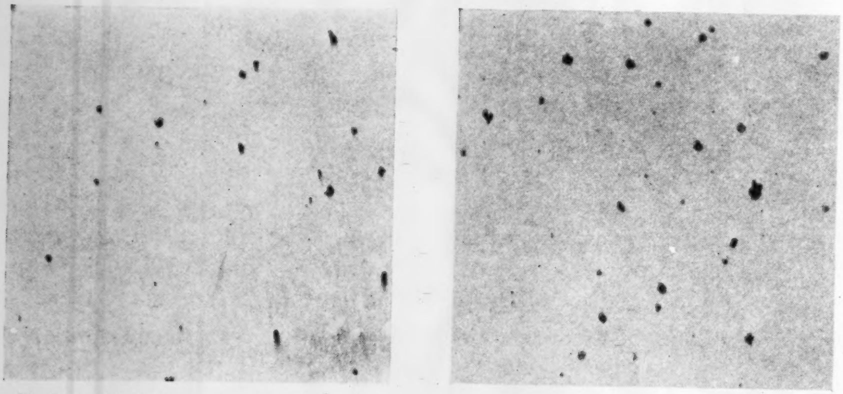
PLATE II.—Inclusions in Cerium Steel. All micrographs unetched (× 100).

after re-drawing. Etching with Stead's reagent indicated that the re-drawn specimens were somewhat more homogeneous than those from the original draws. Steels Nos. 32-37 contained only 0.011 to 0.017 per cent of phosphorus, and notable segregation of phosphorus is unlikely. The slightly banded structure found would be expected in steel not cross-rolled. The effect of re-drawing, as an average on all these tests of specimens cut from plates, was to cause a



(*a*) Molybdenum Steel, C, 0.41, Cr, 0.89, Mo, 0.36. Draw 520° C. (975° F.). Tensile strength, 178,000 lb. per sq. in. Endurance limit, 85,000 lb. per sq. in.

(*b*) Cerium Steel, C, 0.41, Cr, 0.98, Ce, 0.45. Draw 425° C. (795° F.). Tensile strength, 218,000 lb. per sq. in. Endurance limit, 84,000 lb. per sq. in.



(*c*) Stress 82,000 lb. per sq. in.—1,740,000 cycles unbroken. Stress 97,000 lb. per sq. in.—Life 96,000 cycles.

(*d*) Stress 80,500 lb. per sq. in.—Life 80,000 cycles.

Micrographs (*c*) and (*d*): Duplicate Specimens of Plain Carbon Steel No. 1.

PLATE III.—Inclusions in Various Steels. All micrographs unetched transverse sections (× 100).

TABLE V.—EFFECT OF DRAWING TEMPERATURES ON ENDURANCE PROPERTIES.

Steel	Composition, per cent								Temperature of Draw	Time	Brinell	Endurance Limit, lb. per sq. in.
	C	Si	Mn	Ni	Cr	Mo	V	Ce				
32 L	0.37	0.28	0.63	2.49	0.83	....	....	....	475° C. (885° F.)	1 hr	350	85 000
32 LR									Same, then 450 - 475° C. (840 - 885° F.)	1½ hr. more	320	88 000
32 T									Same, then 450 - 475° C. (840 - 885° F.)	1 hr	345	70 000±
34 L 34 LR 34 T 34 TR1 341 TR2	0.44	0.43	0.66	2.44	0.82	0.37	....	....	600° C. (1110° F.)	1 hr	(365)	.....
									625° C. (1150° F.)	1 hr. more	320	69 000
									Same, then 550 - 600° C. (1020 - 1100° F.)	1½ hr. more	295	83 000
									600° C. (1100° F.)	1 hr	(365)	.....
									625° C. (1150° F.)	1 hr. more	320	65 000
									Same, then 500 - 600° C. (930 - 1110° F.)	2¼ hr. more	295	78 000±
									As 34 TR1, but very slowly cooled		295	78 000±
37 L	0.53	0.36	0.65	2.52	0.83	0.34	....	....	610° C. (1130° F.)	1 hr	330	67 000
37 LR1									Same, then 500 - 600° C. (930 - 1110° F.)	2¼ hr	300	89 000
37 LR2									As 37 LR2, but very slowly cooled in salt bath 16 hr		300	87 000
37 T									As 37 L		310	58 000
37 LR1									As 37 LR1		300	70 000±
37 TR2									As 37 LR2		295	70 000
33 L 33 LR 33 T	0.38	0.48	0.61	2.53	0.78	0.75	....	....	625° C. (1175° F.)	1 hr	335	72 000±
									Same, then 600° C. (1110° F.)	2 hr. more	300	84 000
									635° C. (1175° F.)	1 hr	340	56 000
									Same, then 550 - 600° C. (1020 - 1110° F.)	1½ hr	295	71 000
35 L	0.41	0.34	0.58	2.52	0.85	....	0.19	....	560° C. (1040° F.)	1 hr	320	71 000
35 LR									Same, then 410 - 525° C. (770 - 975° F.)	2½ hr. more	300	81 000
35 TR2									As 35 LR1, but very slowly cooled in salt bath	16 hr	300	89 000
35 T									As 35 L		320	60 000
35 TR1									As 35 LR1		300	75 000±
35 TR2									As 35 LR2		300	80 000
36 L	0.36	0.34	0.66	2.46	0.92	....	....	0.19	500° C. (930° F.)	1 hr	340	80 000
36 T									500° C. (930° F.)	1 hr	330	60 000+
												75 000
Average	....	....	....	....	....	....	....	....	....	....	....	69 000±

9-per-cent decrease in Brinell hardness and a 12-per-cent increase in endurance limit simultaneously.

The evil effect of too short a draw and the good effect of a prolonged one is probably most marked in the steels that harden very readily. These steels, Nos. 22, 26 and 32–37, are practically air-hardening steels, but were all oil-quenched in these tests. This problem deserves further study. The indications of our work are that such steels may be inferior in endurance if drawn too little, but are capable of giving superior results if sufficiently drawn. Aitchison(32) says "it is a good and sound rule to make the reheating temperature as high as possible. This has decidedly beneficial effects on the fatigue range and the freedom from internal stress." From the general laws of tempering it would be predicted that a longer time at a given draw temperature would act similarly to an increase in temperature, and this may often bring about greater freedom from internal stress and a higher endurance limit without any marked depreciation of other properties.

One interesting point shown by steels Nos. 10 and 11 is that the endurance limit in the normalized condition (air-cooled from 820–840° C; 1510–1545° F.) is above the static proportional limit. (Fig. 12 (*a*).) The endurance limit is quite normal compared to the tensile strength. The static proportional limit is low because the combination of chromium and molybdenum in these steels makes the steel semi-air-hardening, and a "normalized" steel of this class approaches, in part, to the condition of an untempered air-hardened steel. The stress-strain diagrams of Nos. 10 and 11 in the "normalized" condition are similar in shape to those of an untempered, hardened steel. The amount of internal stress left in these relatively soft steels (around 250 Brinell) does not seem to be great enough to affect the endurance limit though it does pull the static proportional limit down.

A study of Fig. 11 and Table II shows that notwithstanding the oft-repeated claims that vanadium or molybdenum steels are superior to other steels in resisting repeated stress, such claims are without adequate foundation if the comparison of the steels is made on the basis of tensile strength or Brinell hardness. Those claims seem to have been made on the assumption that, because vanadium steels have a high elastic ratio, the high elastic limit for a given ductility must give the steel a high endurance limit, and because for a given elastic limit the molybdenum steels have high ductility, the high ductility must mean high endurance limit. However, according to Moore, McAdam, and other recent workers on endurance, neither elastic limit nor ductility seems to have any direct bearing on endurance, and there is no reason to expect that a plain chrome, a chrome-vanadium, a chrome-molybdenum, a nickel-chrome, a nickel-chrome-vanadium, or a nickel-chrome-molybdenum steel of the same tensile strength should vary in endurance limit. But if we plot as in Fig. 4, from Moore's tests, yield points, Sondericker endurance limits (and, as corroborative of the Sondericker tests, Upton-Lewis tests—although made on improperly necked bars) and the expected endurance limit of 50 per cent of the tensile strength, all against tensile strength, we see that a drop or a rise in the elastic ratio generally coincides with a drop or rise in the endurance ratio. A fine-grained steel usually has a high elastic ratio and it is quite probable that the grain size and other factors which increase or reduce the elastic ratio also affect the endurance ratio.

The factors affecting endurance are obviously complex and the writers do not take the position that when all other factors are eliminated or balanced, the high elastic ratio and ductility of vanadium and molybdenum steels or the strengthening of the ferrite brought about by the addition of nickel to a steel, have no effect on the endurance limit. But, at any rate, these factors are relatively small ones and until many more, and more accurate, tests are made it can only be stated that the specific action of these elements, all of which have been claimed to produce steels superior in resistance to repeated stress, has been exaggerated. At any rate, in Fig. 13, points for steels containing molybdenum, vanadium, or nickel are found to lie among the points for other steels, whether these points are taken from the work of Moore and of McAdam or of the authors.

Lessells(51) has given endurance limits for a carbon steel and another steel of practically identical composition, save for the presence of 0.18 per cent of vanadium. His tests were on cast steels, in the as-cast, annealed and normalized states. The endurance limits were each the average of tests both with the rotating beam and the cantilever types of specimen and show an endurance limit of 42 to 46 per cent of the tensile strength for the carbon, and 48 to 54 per cent with the vanadium steel. If Lessells' figures are plotted on Fig. 13, the points vary from the curve no more than do the other plotted points.

Cast steel may offer a different problem from the wrought steels of Fig. 13, and the finer grain of the vanadium steel should tend toward better endurance; but in view of the fact that the wrought carbon steels usually have an endurance limit of 45 to 55 per cent of the tensile strength, which is all the vanadium steel gave, even this direct comparison of two steels only, leaves the subject open.

Of course if one compares a heat-treated carbon steel with an alloy steel or, say a chrome with chrome-molybdenum steel at the same heat treatment, it can easily be shown that the latter steel is superior in endurance, because the latter steel will harden more thoroughly in the center of a large mass and will not temper so readily at a given draw temperature. But these differences are shown equally in a static tension test. The endurance properties are concordant with the tensile strength obtainable, and are not peculiar to the chemical composition.

It may here be pointed out that our results show (see Table II), as do those of Moore and McAdam, that there is no relationship between endurance limit and either single or repeated impact tests, when the latter are made under such conditions that fracture takes place in a few thousand blows. It can be shown by plots of Izod and Stanton results against tensile strength or Brinell hardness that neither molybdenum nor vanadium alters the characteristic shape of these curves, and that a given class of alloy steels shows about the same impact properties for a given hardness, irrespective of its composition.

EFFECT OF NON-METALLIC INCLUSIONS AND OTHER INHOMOGENEITIES

There is one exception to such a statement, whether in reference to endurance or to impact. In our work, in each class of steel studied, a steel containing cerium was included. These cerium steels were always dirty; that is, full of non-metallic inclusions. The cerium steels gave, on the average, lower results on endurance tests that would be predicted from the tensile strength. In Fig. 13 the points for the cerium steels are plotted as triangles. Some of the triangles are on the curve, especially in the softer steels, but most of them are distinctly below it. Likewise, when the Stanton and Izod figures are plotted, the cerium steels, though now and then giving normal results, on the average fall below the other steels.

The endurance results on a cerium steel not only often average low, but they generally show a wider "scatter" than the other steels. Fig. 12 for steel No. 36 L shows a characteristic example of a cerium steel. One specimen at 86,000 lb. per sq. in. (which should be the endurance limit of a 340 Brinell steel) stood 1½ million cycles unbroken. Another at 81,000 lb. per sq. in. broke after 88,000 cycles. Three out of seven specimens broke away from the point of minimum section. Moore(2) considers that a fatigue failure starts from some point at which there is a local overstress due to a crystal being so located that the line of application of stress runs along a slip plane while other adjacent crystals are more favorably oriented, or where some surface scratch, internal notch, inclusion, or flaw acts as a local "stress-raiser" to intensify the stress above that calculated for the material as a whole on the assumption that it is uniform. In his latest tests(3) he has worked with a dirty steel and finds that while some specimens give the results to be expected for the tensile strength, others give low results. McAdam(9) also comments on the lower endurance of transverse specimens compared to longitudinal ones and concludes that this is due to the effect of the non-metallic inclusions. Work on the effect of inclusions on endurance is in progress at Annapolis(48). Mathews(36) says: "Freedom from internal flaws and surface irregularities is far more important in members subjected to repeated stress than in those subjected to but few repetitions of load." Lea(13) points out that a slag inclusion or similar internal defect tends to act, under repeated stress, as if it were a crack already started before the test began. Haigh(39) ascribes most results that are lower than would be expected from the tensile strength, to "slag inclusions or dirtiness of the metal."

Fremont(40) says that failure under alternating dynamic stresses is commonly due to heterogeneity of the metal and especially to the presence of inclusions. Aitchison(32) finds that transverse specimens give lower endurance values than longitudinal ones. He sharply differentiates between ideal endurance values taken as a given percentage of the tensile strength, and the real or practical values, and ascribes the discrepancy to "local imperfections" of which, he says, the group including slag, non-metallic inclusions, and the like, is the most potent. All metallurgists who have made any considerable number of endurance tests seem to agree that dirty steel is unreliable under repeated stress.

The element of chance comes very strongly into endurance testing with necked round specimens on the Upton-Lewis machine because two "mathematical points" only, on opposite sides of the specimen, are stressed to the maximum in reversed bending. In Moore's Sondericker tests an extremely small surface is so stressed, in McAdam's rotary bending tests of conical specimens a larger surface is so stressed, while in axial tension-compression tests the whole cross-section is so stressed. McAdam's test piece seems to give results a little lower than Moore's test piece, while axial tests run very much lower. McAdam(7) states that close to the endurance limit, a decrease of stress of 1.5 per cent corresponds to a hundredfold increase in life. McAdam's tapered test pieces stress, to within 1.5 per cent of the maximum, an area of 2.3 sq. in. and a volume of

0.085 cu. in. Moore's Sondericker type specimens stress an area of 0.2125 sq. in. and a volume of 0.00045 cu. in. A tension test piece equivalent to the fully stressed volume of McAdam's rotary bending specimen would be about the size of the lead of an Eversharp pencil, while that equivalent to Moore's would go in the eye of a sewing needle. The volume so stressed in round necked Upton-Lewis specimen is still smaller. An equivalent tension specimen would be of microscopic dimensions. With such tiny volumes fully stressed, it is obvious that microscopic inclusions are really big in comparison to the volume of material actually under test, and that chance has much to do with the dirtiness or cleanliness of so small a volume. The incidence of chance is, of course, in the location of the inclusion with reference to the point of maximum stress. The round Upton-Lewis specimen is probably not so well adapted as the others to show up differences due to dirty steel because of the small area exposed to maximum stress.

The difficulty of detecting the presence of an inclusion at the nucleus of fracture has already been pointed out. Nevertheless, in the cerium steels the inclusions are so numerous that it seems quite justifiable to ascribe the low results to the presence of inclusions. Plate II (*a*) and (*b*) shows the extreme met in the cerium steels studied. Plate II (*c*) and (*e*) shows intermediate degrees of dirtiness. The cerium content, when above about 0.25 per cent, varies in a given ingot, being highest at the top and lowest at the bottom and the inclusions are most numerous at the top. The sulfur content, although not over 0.03 per cent in any of the cerium steels tested, varies in the same way and the inclusions probably contain both cerium and sulfur. The inclusions do not roll out into threads or plates as manganese sulfide does. They are arranged in lines to a greater or less degree, and laminated fractures are common, but the individual inclusions tend to remain approximately globular. They thus do not take on the sharp leaf-form of an elongated manganese sulfide inclusion, and they appear to have scarcely any more effect on a transverse specimen than on a longitudinal one. The cerium steels indeed showed rather less "woodiness" on transverse fractures than the other steels. It is not surprising that the cerium steels show low endurance and erratic results, when we note how dirty they are; the surprising thing is that they do not fall farther below the results of cleaner steels.

Plate III (*a*) and (*b*) shows a comparison between a molybdenum steel which was shown by examination of many surfaces of many specimens to be consistently clean, and a cerium steel which was consistently dirty. It is necessary to heat treat the dirty steel to

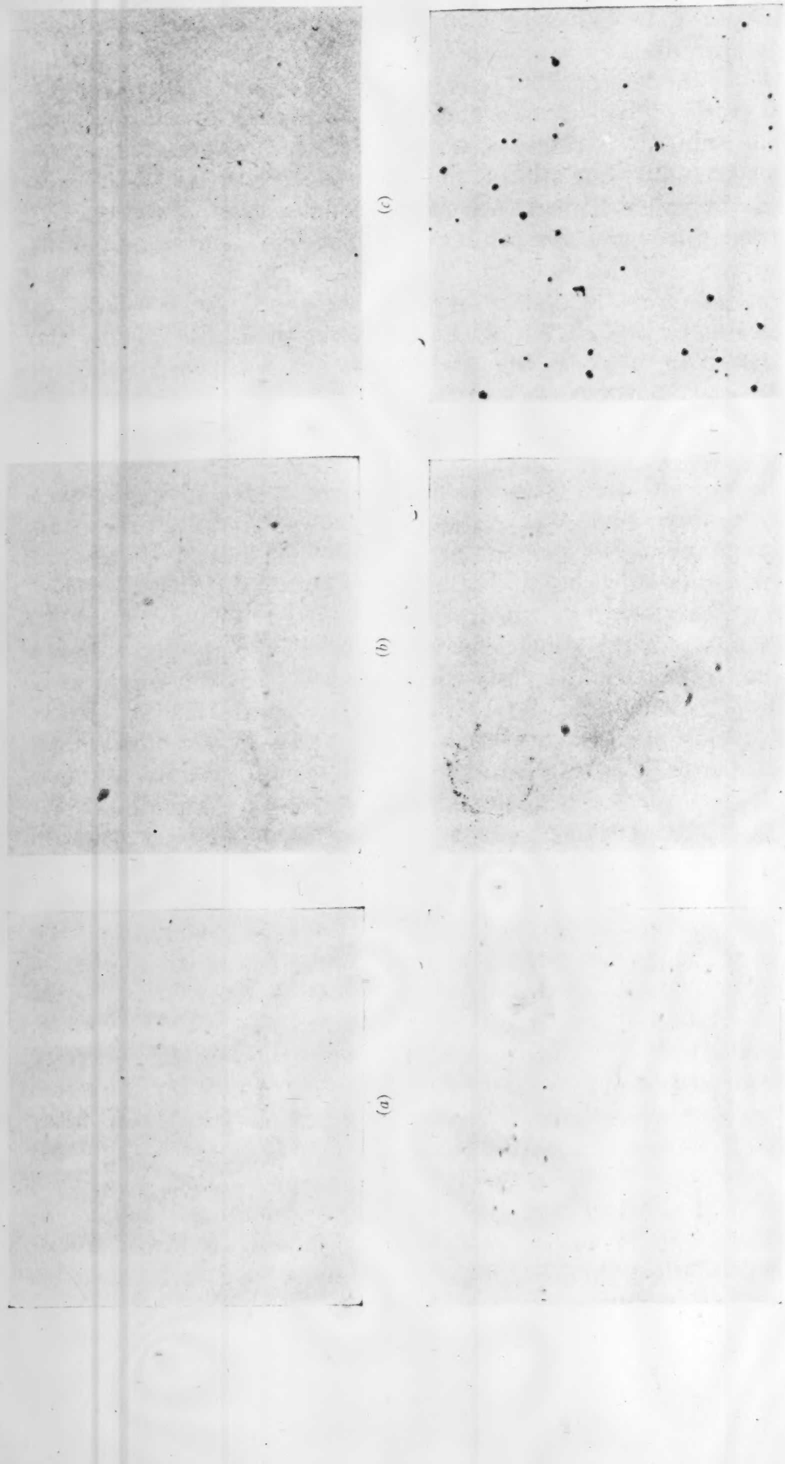
40,000 lb. per sq. in. higher tensile strength to get the same endurance limit as shown by the clean one.

Some of the low results appear to be rather definitely ascribable to dirty steel. Plain carbon steel No. 1 showed low and erratic endurance values. A retest of another set of endurance specimens gave higher results, but still on the low side. Plate III (*c*) and (*d*) shows another angle of relation between dirtiness and endurance.

On the other hand, low results were sometimes obtained on steels that were not consistently dirty. Steel No. 10, draw 2, on which too few specimens were available for adequate test, gave a couple of specimens indicating an endurance limit lower than called for by the curve of Fig. 13, while at the other draws the results were normal. Plate IV shows a half-dozen sections from different specimens of the steel, five of which would class it very clean and one as decidedly dirty.

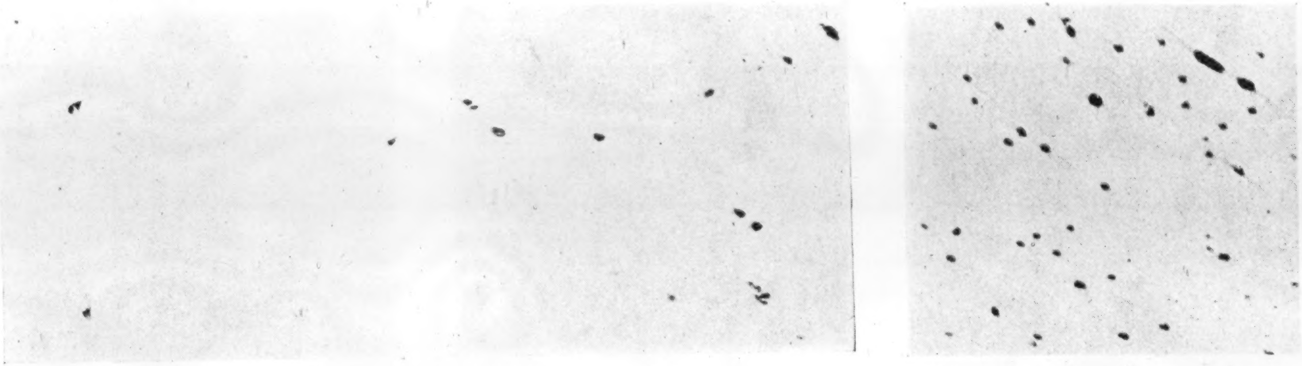
Plate V (*a*), (*b*) and (*c*) shows sections from a steel giving average or better results. Plate V (*d*), (*e*) and (*f*) shows variability in cleanliness of a commercial electric furnace chrome-vanadium steel (No. 55) which gave endurance results both slightly above and slightly below the average curve on different draws.

If a sharp-pointed inclusion lies near the point of maximum stress but not exactly at it, and the local excess stress it produces is still below the endurance limit, it should not cause failure. Moreover, an inclusion so oriented that its tip points in the direction of the applied stress, does not raise the local stress, just as a longitudinal scratch does not. An example of this is shown in Plate VI (*a*), (*b*) and (*c*) from a bar sent by Moore for examination. This steel (Moore's No. 3 normalized) has an endurance limit of 42,000 lb. per sq. in. The large inclusion shown lay in the longitudinal direction, with its tip 0.01 in. below the surface and about 0.1 in. away from the point of minimum section. The test piece was run at 40,400 lb. per sq. in. and the calculated stress at the tip of the inclusion would be about 37,200 lb. per sq. in. The specimen ran over 100 million cycles unbroken. The longitudinal inclusion evidently did not raise the local stress as much as the 15 per cent required to bring the stress up to the endurance limit. Strengthening by understressing may have raised the endurance limit, however, in this case. A duplicate specimen also run at 40,400 lb. per sq. in., failed at about 3½ million cycles. As Plate VI (*d*) and (*e*) shows, there were some deep circumferential scratches on this specimen, the finish being decidedly poorer than that of the unbroken piece. The short-lived and the long-lived specimens aside from the one large inclusion, which was not at



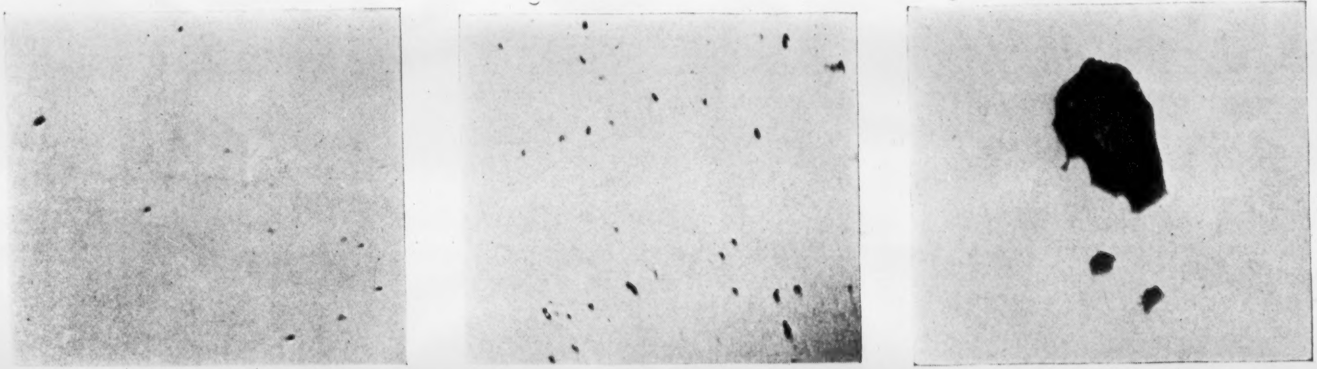
(a) (b) (c) (d) (e) (f)

PLATE IV.—Showing Variation in Cleanliness in a Chrome-Molybdenum Steel (No. 10) made in the Bureau of Mines Laboratory. Each micrograph shows a different specimen rolled from the same ingot. All micrographs unetched transverse sections (× 100).



(a) (b) (c)

Micrographs (*a*), (*b*) and (*c*), Chrome-Molybdenum Steel No. 48.



(d) (e) (f)

Micrographs (*d*), (*e*) and (*f*), Chrome-Vanadium Steel No. 55.

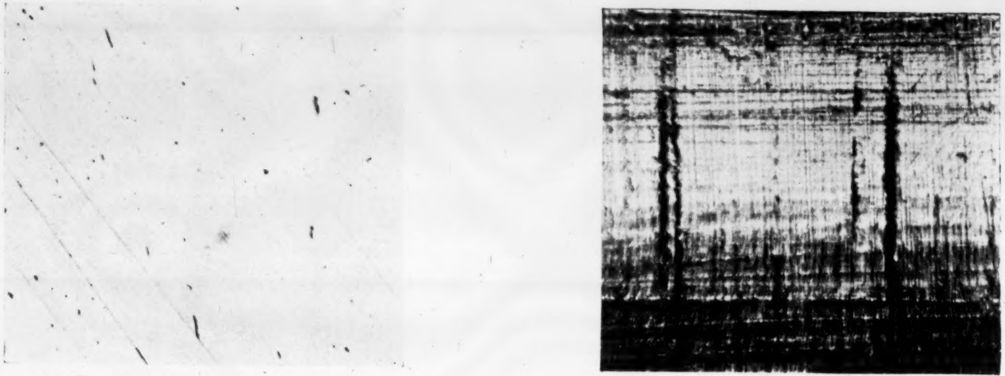
PLATE V.—Variations in Cleanliness of Electric-Furnace Steel from Commercial Sources. All micrographs unetched transverse sections (× 100).

(*a*) Unetched transverse section (× 200).

(*b*) Unetched transverse section (× 100).

(*c*) Surface appearance at point of minimum section (× 50).

Micrographs (*a*), (*b*) and (*c*), from specimen stressed at 40,400 lb. per sq. in.; unbroken after 100,000,000 cycles.



(*d*) Unetched transverse section (× 100).

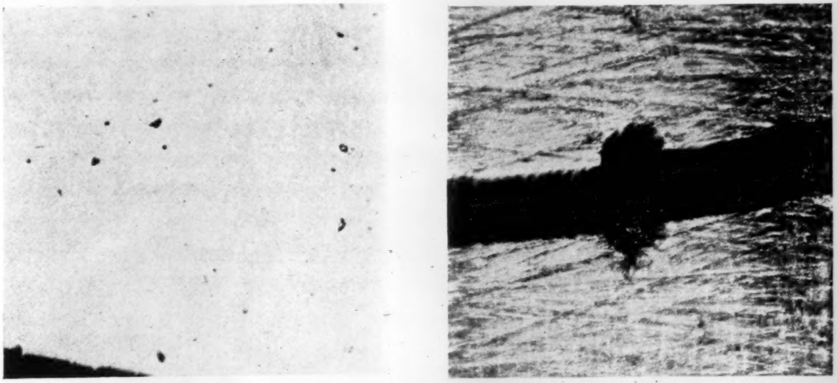
(*e*) Surface appearance at fracture (× 50).

Micrographs (*d*) and (*e*), from specimen stressed at 40,400 lb. per sq. in.; broken at 3,500,000 cycles.

PLATE VI.—Inclusions in Duplicate Specimens of Moore's No. 3 Steel.

the point of maximum stress, appeared to contain about the same number of inclusions.

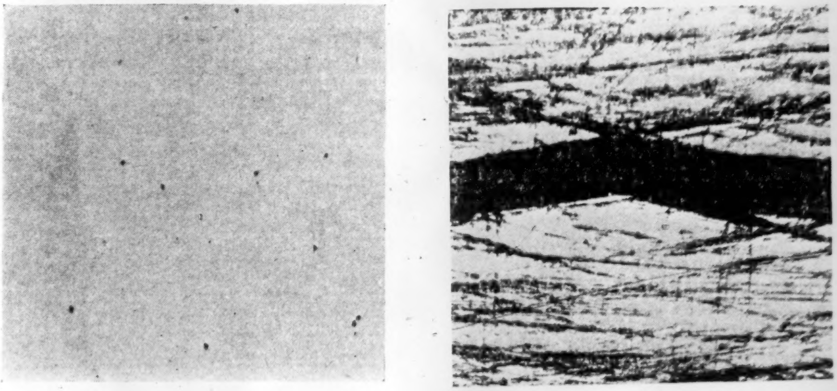
Another pair of Moore's specimens (No. 7, 3.5 per cent nickel, heat treatment B) were examined. The endurance limit of this steel is 63,000 lb. per sq. in. One specimen at 65,000 lb. per sq. in. lasted 492,000 cycles before cracking. The piece was removed before



(*a*) Unetched transverse section (× 100).

(*b*) Surface appearance of specimen at fracture (× 100).

Micrographs (*a*) and (*b*), from specimens stressed at 65,200 lb. per sq. in.—Life, 492,000 cycles.



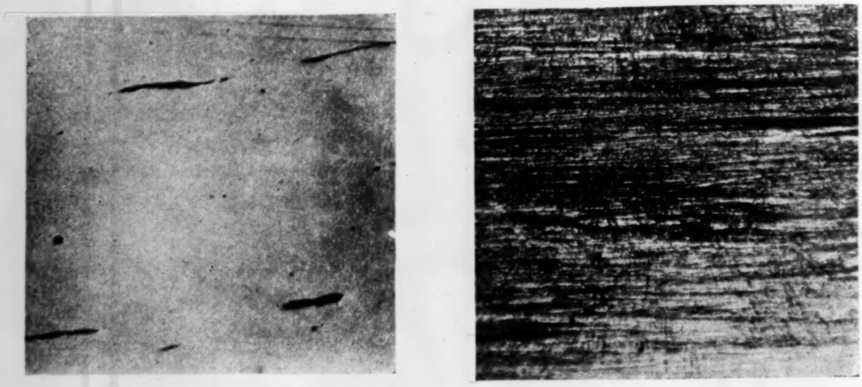
(*c*) Unetched transverse section (× 100).

(*d*) Surface appearance of specimen at fracture (× 100).

Micrographs (*c*) and (*d*), from specimen stressed at 68,000 lb. per sq. in.—Life, 1,359,000 cycles.

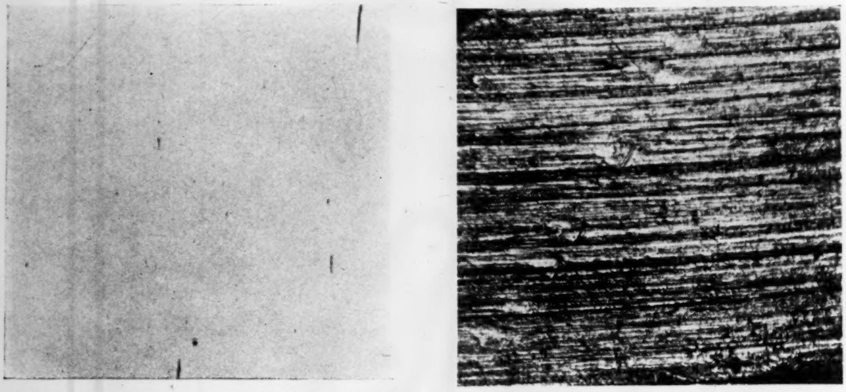
PLATE VII.—Inclusions in Duplicate Specimens of Moore's No. 7 Steel.

fracture was complete. The crack was not at the point of maximum stress, but at a point at which the indicated stress is about 61,600 lb. per sq. in., that is, below the endurance limit. As Plate VII (*b*) shows, the nucleus of fracture was at a point from which an inclusion seems to have dropped out, or at a surface mar. The presence of inclusions in the steel near the fracture as shown in Plate VII (*a*) makes it probable that the pit shown was originally filled by an in-



(*a*) Unetched longitudinal section (× 100). (*b*) Surface appearance at fracture (× 50).

Micrographs (*a*) and (*b*), from specimen stressed at point of failure to 46,500 lb. per sq. in.—Life, 6,500,000 cycles.



(*c*) Unetched longitudinal section (× 100). (*d*) Surface appearance at fracture (× 50).

Micrographs (*c*) and (*d*) from specimen, stressed at point of failure to 50,000 lb. per sq. in.—Life, 250,000,000 cycles.

Plate VIII.—Inclusions in Duplicate Specimens of McAdam's Molybdenum-Nickel (H-1) Steel.

clusion. A duplicate specimen, Plate VII (*c*) and (*d*), cracked at the point of minimum section after 1,359,000 cycles at 68,000 lb. per sq. in. and was also removed before complete fracture. In this case the crack followed surface scratches which were transverse or nearly so. This specimen was cleaner than the other. The inclusions seem to have determined the nucleus of failure in the former specimen, the scratches in the latter.

A pair of specimens kindly sent on by McAdam were similarly examined. Plate VIII (*b*) shows the surface finish at fracture of a piece stressed at 49,000 lb. per sq. in., but breaking at a point corresponding to about 46,500 lb. per sq. in. after 6,500,000 cycles. Inclusions are present (Plate VIII (*a*)). A duplicate specimen broke at the point of maximum stress, at 50,000 lb. per sq. in. after 250,000,000 cycles. This specimen, as Plate VIII (*c*) and (*d*) show, was both cleaner and had a better surface finish than the specimen of shorter life.

Inclusions appear to act as local stress-raisers. Since they are probably hard as compared with the steel matrix in which they are imbedded, they may be considered as "internal notches," or, better, as inserted wedges of hard material. The magnitude of their local effect on stress is probably a function of the radius of curvature of their edges and of their orientation with respect to the direction of stress application. Thus, globular inclusions will in general be less effective as stress-raisers than inclusions which have been flattened, during the process of fabrication, to leaf form and present a knife-like edge having an infinitely small radius of curvature. The stress density at an internal notch of this kind can be mathematically shown to approach infinity as a limiting value, when the notch crosses the line of stress application. Therefore, if we have a non-metallic inclusion so shaped, so oriented, and so placed with respect to the direction of stress application that the local effective stress rises above a critical value (the endurance limit) we have a picture of the mechanism by which fatigue failure may start even though the nominal computed stress for the specimen is below the actual endurance limit of the steel composing the matrix. Once started, fatigue failure proceeds from this minute crack in a manner well understood and well illustrated by the effect on endurance properties of external notches, hardening cracks, deep tool marks, or fillets of small radius.

ENDURANCE AND ENGINEERING DESIGN

The most glaring cause of fatigue failures in practice is poor engineering, which fails to provide proper fillets. If that cause of failure is avoided, failure may occur because of transverse scratches, usually tool marks. These may also be avoided if one is willing to pay the price and finish by grinding in a direction parallel to the axis of principal stress, or, better still, of polishing highly stressed parts to remove all tool marks. But the designer or the machinist cannot remove the inclusions. Hence dirty steel, stressed in such a direction that the inclusions act as stress-raisers, is unreliable under repeated stress unless a sufficiently large factor of safety is allowed to take care of the worst case. Conversely, when, as in airplane work, weight must be kept down and the factor of safety made small, dirty steel is dangerous.

Chance is so predominant in the location of inclusions at the crucial section of a repeatedly stressed part that in a given case a piece of dirty steel may happen to have no dangerous stress-raisers at the crucial section, and a piece of relatively clean steel may have them there. Good practice, however, will select the cleanest possible steel for parts subject to repeated stress.

There are many indications that the endurance properties of the harder heat-treated steels are more injured by fillets of small radius, by surface scratches, and by inclusions, than are softer steels; that is, strong steels are more sensitive to all classes of local stress-raisers. Rosenhain(41) suggests that inclusions probably act as nuclei for quenching cracks in heat treatment. Hoyt(38) points out that in excessively brittle materials, like glass, the multiplication of the computed maximum stress by notches is greater than in softer materials. In soft rivet steel, for example, it is likely that inclusions are not very harmful, whereas in spring steel they certainly are. Even a soft steel may be affected by them and Moore's screw stock (Moore's steel No. 50, 0.20 per cent carbon, 0.095 per cent sulfur, annealed at 700° C. (1300° F.)) is probably a case in point. This gave an average endurance limit of 29,000 lb. per sq. in., some specimens stressed at 28,000 to 29,000 lb. per sq. in. lasting 60 million cycles unbroken, but one specimen at 25,000 lb. broke after $3\frac{1}{4}$ million cycles.

Howe(42) comments on the reported use of high-sulfur screw stock for motor-car steering posts by saying: "Such practice should be a felony." He also says: "Because toughness and slag both cause fiber, some befogged ones infer that slag causes toughness." Notwithstanding Howe's discussion of eight years ago, we find a recent patent(43) claiming that, while the presence of foreign substances in steel is injurious for the usual structural purposes, for use where the steel is subjected to fatigue and vibratory stress it is desirable to impart to the steel a definite fibrous structure by deliberately incorporating slag, brick dust, or clay in the steel when originally cast! Such a suggestion is entirely opposed to the indications of endurance tests.

ENDURANCE AND INHOMOGENEITIES IN NON-FERROUS METALS

It might be expected that any sort of inhomogeneity in an alloy would cause some local increase or decrease in stress, according to the modulus of elasticity, the shape and distribution of the different inhomogeneities and various other factors tending toward the creation of "stress whorls." Pearlite uniformly distributed in ferrite gives an alloy stronger than pure ferrite. Slag inclusions weaken sorbite. How would the effect of uniformly distributed, very soft inclusions or inhomogeneities in a harder matrix differ from that of hard ones in a softer matrix?

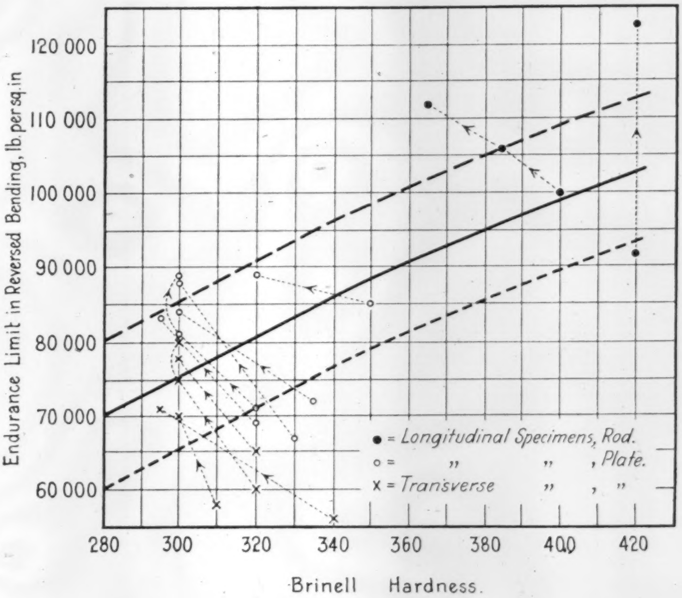


FIG. 14.—Relation Between Endurance Limit and Brinell Hardness Showing the Effect of Prolonged Drawing on Nickel-Chromium, Molybdenum and Vanadium Steels. See Table V.

The full line is the average curve of Fig. 13; the broken lines show the usual range of "scatter" above and below that curve. The endurance limit for the shortest draw time has been plotted against Brinell hardness and that point is connected by a line, bearing an arrow, with the point or points for endurance limit for longer draw or draws.

Steel specimens did not seem capable of yielding the answer to this question, so in the hope of getting some further information on the general subject of inhomogeneities and their effect on endurance, it was decided to study a couple of non-ferrous materials with inhomogeneities which would be rather more regularly distributed than in the case of slag in steel.

For this purpose two series of specimens were selected—one of pure copper with varying contents of oxygen, the other of brass with varying contents of lead. The first is more or less analagous to the ferrite-pearlite combination in steel. Cuprous oxide is soluble in solid copper. It forms a eutectic at about 3.5 per cent Cu_2O (0.38 per cent oxygen), and ordinary tough pitch copper with 0.04 per cent oxygen contains approximately 10 per cent eutectic. Copper oxide is harder and more brittle than copper. Antisell(44) states that, tested as No. 12 annealed wire, copper of varying oxygen content varies in physical properties as follows:

Oxygen, per cent	Tensile Strength, lb. per sq. in.	Elongation,[1] per cent	Number of Bends[2]	Conductivity, per cent
0.200................	37 340	28	21	98.25
0.050................	36 000	35	30	100.30
0.015................	34 000	37	35	100.80

The question is, does the endurance at lower stresses, with little or no plastic deformation, drop with increasing oxygen content as does the resistance to bending at stresses involving great plastic deformation? Hanson, Marryat and Ford(45) have tested rolled $\frac{5}{8}$-in. rod annealed at 700° C. (1290° F.), with the following results:

Oxygen, per cent	Tensile Strength, lb. per sq. in.	Elongation,[3] per cent	Reduction of Area, per cent	Impact Value, Izod, ft-lb.	Conductivity, per cent	Endurance Limit, Wöhler Test-Rotary Bending, lb. per sq. in.
0.016	31 800	53½	77	46	101.4	11 400
0.04	32 000	50	71½	45½	101.6	13 650
0.06	32 300	56	70	47½	101.5	13 000
0.09	33 000	52	64½	45	100.6	11 850
0.17	34 300	49	58	31	99.0	11 200
0.36	37 100	34½	38½	15¾	96.2	11 400

No details of the endurance tests are given, nor is it even stated to how many cycles the tests were carried. Their criterion for reaching an endurance limit cannot even be guessed at. H. F. Moore is now studying annealed copper, but no data on the endurance of hard-drawn copper have been obtained.

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[1] Gage length not stated.

[2] The bend test is the number of 90-deg. bends on the Capp bending machine.

[3] Gage length: $4 \times \sqrt{\text{area}}$.

Haigh(46) has given axial tension-compression tests on Muntz metal and Naval brass in the hard-drawn and annealed conditions, but only one test was carried to more than $2\frac{1}{2}$ million cycles. The S-log N plots show a curvature, but since R. R. Moore(47) shows that non-ferrous alloys such as cast manganese bronze, rolled electron metal and duralumin may require 20 to 200 million cycles to show anything approximating an endurance limit and H. F. Moore(3) does not find an endurance limit in monel metal at 300 million, Haigh's test cannot be given very much weight.

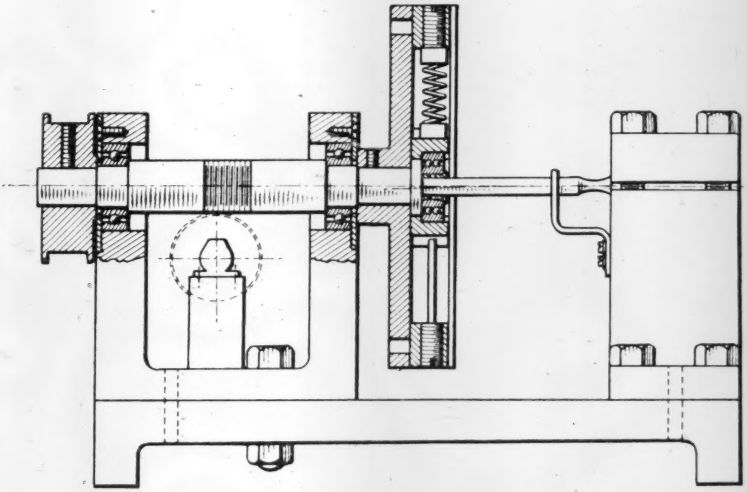

FIG. 15.—Reversed Stress Testing Machine (Spring Load Rotary Type) U. S. Bureau of Mines. From Design of Materials Testing Laboratory, University of Illinois Experiment Station.

Lee(26, p. 80) and Rosenhain (17) have both found evidence of the strengthening effect in aluminum alloys, but no data have been found to show whether or not this is to be expected in brass and copper.

The non-ferrous endurance tests were made on two rotary spring testing machines of the type described by Moore(2), in which one end of the test piece is gripped in a vise and the other end is moved through a circular path by an eccentrically-placed, self-aligning ball bearing. The radius of the circle described by the end of the test piece is determined by variation in the pressure applied to the ball bearing by a calibrated engine indicator spring (Tabor type). The testing machines used were built from a design developed by Moore at the University of Illinois Engineering Experiment Station. A partial cross-sectional view of the machine is shown in Fig. 15, which shows the essential details of construction. Since these machines were built, Tuckerman(53) has found that self-aligning bearings, in the Sondericker type machine, give less satisfactory results than are obtained through the use of a design in which alignment is maintained by mounting a deep-groove ball bearing in a carrier supported on trunions. The deviation from average in some of our data may be traceable to this feature of the design.

The machines at first operated at 1750 r.p.m. and later at 2400 r.p.m. They were provided with an automatic stopping device which exercised control of the motor circuit through a six-volt relay circuit in which the contact elements were the test piece and an annular contactor concentric with the piece and so located that the amplitude of motion was insufficient to bring about contact during normal operation but did so promptly upon fracture of the specimen.

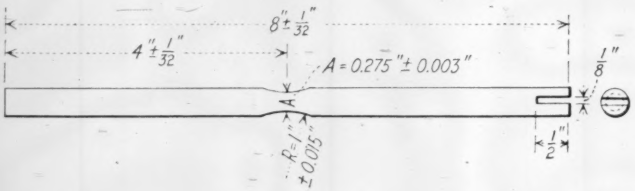

Fig. 16.—Test Piece for Determination of Endurance Limit of Copper and Brass.

It will be noted that the design of the machines is such that the accuracy of the stress computations is dependent upon the obtaining of coincidence, within close limits, of the axis of the fixed end of the test piece with the axis of the shaft driving the chuck. With the facilities available it was found impossible to attain a better alignment of these parts than 0.001 in. This deviation from coincidence, with the springs now in use, corresponds to a variation in stress applied to the specimen of ±100 lb. per sq. in. at a stress of 19,000 lb. per sq. in., and of ±200 at a stress of about 24,000 lb. per sq. in. These stresses are mentioned as representative of the values used in testing copper and brass, respectively.

The test piece adopted for this portion of the investigation was of 0.390-in. diameter, ground to size on centers, and necked down at the point of maximum stress to 0.2750 in. on a 1-in. radius. The details and dimensions of the test piece are shown in Fig. 16 (see Fig. 5*c*).

In order to define closely the material used for the endurance tests, determinations were made of the static mechanical properties of the leaded brass and of the oxygenated copper. Data on the chemical properties and the thermal and mechanical history were supplied by the makers.

STATIC MECHANICAL PROPERTIES OF BRASS

The brass series was selected to give the same copper-zinc ratio with lead varying in steps from 0 to 3½ per cent. The brass was made by the Bridgeport Brass Co. and supplied through the courtesy of W. R. Webster. It was melted in the Ajax-Wyatt electric furnace, cast in 7-in. diameter billets and extruded to 0.697 in. through a five-hole die. Rods were then drawn down to 0.400 in. in diameter in five reductions with intermediate anneals. The reductions were, respectively, 27.5, 17.4, 24.5, 13.5 and 16.3 per cent. The chemical analysis (by Bridgeport Brass Co.) follows:

LOT NO.	CU	ZN[1]	PB	FE	CU-ZN RATIO	EQUIVALENT STRAIGHT BRASS CU	EQUIVALENT STRAIGHT BRASS ZN	DEVIATION OF CU FROM AVERAGE
2......	61.60	38.31	0.06	0.03	1.61	61.66	38.34	−0.09
5......	61.54	37.89	0.53	0.04	1.62	61.92	38.08	+0.17
4......	61.03	37.89	1.58	0.03	1.63	62.12	37.88	+0.37
3......	59.58	37.78	2.61	0.03	1.58	61.34	38.66	−0.41
1......	59.40	37.14	3.43	0.03	1.60	61.71	38.29	−0.04
Average..........						61.75	38.25	

[1] By difference.

All compositions in per cent.

The mechanical properties were given by the Bridgeport Brass Co. as determined on a specimen 0.350 in. in diameter and 2-in. gage length. "Elastic limit" was determined by dividers. Since it is important to know the elastic properties more closely than the divider method can indicate, further tests were made by the Bureau of Mines. A special connector was made by which two Berry strain gages could be used on opposite sides of the specimen. As the specimens were too small to be shouldered, it was necessary to thread the ends in order to hold them in the self-aligning ball and socket grips of a 20,000-lb. hand-operated Olsen testing machine, made available through the courtesy of Sibley College, Cornell University. The ends were threaded with a ⅜-in. S.A.E. thread, and the test section was 0.300 in. in diameter by 2-in. gage length. The area at the base of the threads was too nearly that of the breaking section and four of the annealed brass specimens broke in the threads instead of in the test section.

The stress-strain curves, averaged from four sets of readings (one on each side of two specimens), are shown in Fig. 17. These show that any difference in the proportional limit on the brass samples is scarcely greater than the limit of accuracy of the method, since the first detectable deviation of the stress-strain diagram from a straight line is between 25,000 and 27,000 lb. per sq. in. on all the hard brass samples. It is recognized that with more delicate apparatus for measuring strain, the "proportional limit" would be lower, and theoretically might go down almost to zero stress, but even these tests will serve to show the comparative behavior of the materials. If we use the "offset method," taking as the engineering elastic limit a permanent set of 0.0001 in. per inch, we get 28,000 to 30,000 lb. per sq. in. The general trend of the proportional limit seems to be to drop slightly with increasing lead content.

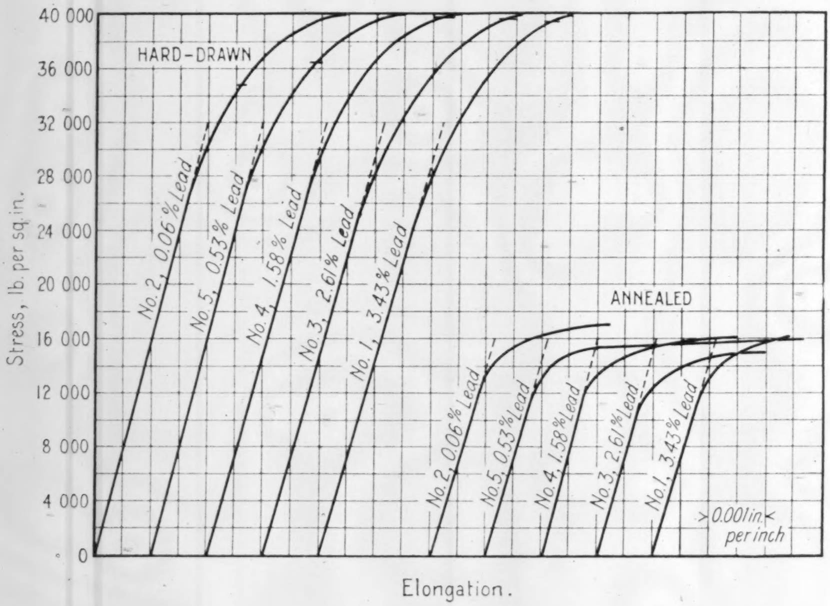

FIG. 17.—Stress-Strain Curves for Hard-Drawn Brass Containing Various Percentages of Lead. Copper-Zinc Ratio: 61.75 — 38.25.

The results on the brasses are given in Table VI. When the specimen broke at a punch mark or in the threads the observed elongation is given, followed by a plus mark when the result would have been higher on a bar breaking within the test section. The Bridgeport Brass Co., figures show the true ductility but are not sufficiently accurate as to the elastic limit, while the Bureau of Mines' figures show the proportional limit with a fair degree of accuracy but the ductility figures are not accurate unless the specimen broke within the test section. The Bureau of Mines' tests were made at a slow rate of loading. It was seen that in the hard-drawn specimens the 0.06-per-cent-lead and 0.53-per-cent-lead brasses were not affected by the external notches (threads), while at 1.58 per cent lead one of the two specimens broke at the punch mark and all the specimens of lots still higher in lead broke at the punch mark.

TABLE VI.—MECHANICAL PROPERTIES OF HARD-DRAWN BRASS CONTAINING VARIOUS PERCENTAGES OF LEAD.

		Determined by Bridgeport Brass Co.				Determined by Bureau of Mines				Fracture	
Lot No.	Lead, per cent	Tensile Strength, lb. per sq. in.	Elastic Limit (Dividers), lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Tensile Strength, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Location	Kind
2	0.06	60 400	34 700	39.5	73	58 600	27 000	41	73	middle third....	cup
						59 400	27 000	42.5	74	middle third....	cup
5	0.53	59 400	36 500	39	62.5	56 500	27 000	38.5	68	middle third....	cup
						58 700	27 000	40	68.5	middle third....	cup
4	1.58	58 300	39 800	38.5	59	57 900	26 000	40	63.5	middle third....	cup
						57 500	26 000	33+	42.5+	at punch mark..	chisel
3	2.61	59 200	39 700	37.5	53	57 600	25 000	22.5+	40.5	at punch mark..	oblique
						58 500	25 000	30.5+	53.5+	at punch mark..	oblique
1	3.43	58 100	39 400	36.5	50.5	58 000	25 000	23.5	26+	at punch mark..	oblique
						56 600	25 000	26+	29.5+	at punch mark..	oblique

STATIC MECHANICAL PROPERTIES OF COPPER

The copper specimens Nos. 1 to 4 inclusive, representing stages in the refining of a single heat, were obtained through F. L. Antisell of the Raritan Copper Works, and were rolled and drawn through the courtesy of the Bridgeport Brass Co. Specimen No. 5 was cast by the Bridgeport Brass Co. The specimens were hot-rolled from the billets to $\frac{25}{32}$ in. in diameter, and drawn to 0.400 in. in diameter in four reductions with intermediate anneals, at 550 to 600° C. (1025 to 1110° F.). The bars were pickled after each anneal. The reductions were, respectively, 26, 36, 23.8 and 16.3 per cent. The bars were straightened in a 12-roll straightener.

Following is the analysis for specimens Nos. 1 to 4, as made by the Raritan Copper Works. The conductivity was determined by the Bridgeport Brass Co. on No. 10 B. & S. gage (0.102-in. diameter) wire drawn from 0.400 in. with the last anneal at 0.203-in. diameter.

LOT NO.	CU	O	S	AS	SB	NI	FE	AG	CONDUCTIVITY PER CENT
1......	99.750	0.240	0.0005	0.0015	0.002	0.0015	0.002	0.001	94.6
2......	99.896	0.094	0.0001	0.0015	0.002	0.0015	0.002	0.001	97.9
3......	99.940	0.049	0.0002	0.0015	0.002	0.0015	0.002	0.001	98.9
4......	99.954	0.036	0.0002	0.0015	0.002	0.0015	0.002	0.001	99.6

All composition in per cent.

TABLE VII.—MECHANICAL PROPERTIES OF HARD-DRAWN COPPER WITH VARIOUS PERCENTAGES OF OXYGEN.

Lot No.	Oxygen, per cent	Tensile Strength, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Fracture		Breaking Load (on Original Area), lb.
						Location	Kind	
1	0.240	40 200	20 000	26.5	48.5	outer third......	cup	....
		41 000	20 000	15.5+	39+	at punch mark..	chisel	....
2	0.094	37 000	20 000	27	61.5	outer third......	cup	....
		39 000	20 000	26.5	64.5	outer third......	cup	....
3	0.049	37 600	19 500	28.5	67.5	outer third......	cup	....
		37 600	19 500	30	67.5	outer third......	cup	....
4	0.036	37 600	19 000	27.5	72	outer third......	cup	....
		37 800	19 000	32.5	73.5	outer third......	cup	....
5	....	36 000	17 000	31	81.5	outer third......	cup	18 400
		35 000	17 500	31	84	outer third......	cup	16 700
		37 000	18 000	29	84	outer third......	cup	18 200
		36 400	18 000	32	84	middle third.....	cup	15 500
Average	No. 5....	36 000	17 500	32	84	....	cup	17 000

The deoxidizing agents used on No. 5 were 2½ oz. of phosphor copper (10 per cent phosphorus) and 1 oz. of manganese copper (28 per cent manganese) per 100 lb. These were added 3 minutes before pouring and vigorously stirred with a plumbago stirrer for 2 minutes. The metal was poured at about 1230° C. (2250° F.). The additions amount to 0.0156 per cent phosphorus and 0.0175 per cent manganese. The Bridgeport Brass Co.'s analysis for No. 5 copper shows:

Copper, per cent........................	99.919	
Manganese, "	0.032	(0.017 charged)
Phosphorus,"	0.010	
Iron, "	0.058	
	100.019	

The manganese found is more than that added. The Bridgeport Brass Co. states that their analyses and the analyses of consulting chemists to which similar samples have been sent, invariably show more manganese than that added. No explanation of this fact is available.

The Raritan Copper Works analyzed No. 5 and found 0.0385 per cent of oxygen, which does not agree with the expectation that this sample would be oxygen-free. Microscopic examination, however, fails to show any cuprous oxide. On account of the presence of phosphorus, this specimen does not fall in exactly the same class as Nos. 1 to 4. It will be referred to as "No. 5" rather than as oxygen-free copper. The conductivity of No. 5 was 81 per cent.

The physical properties were determined by the Bureau of Mines on specimens of the same dimensions as the brass stock. The stress-strain curves are shown in Fig. 18 and the data are given in Table VII.

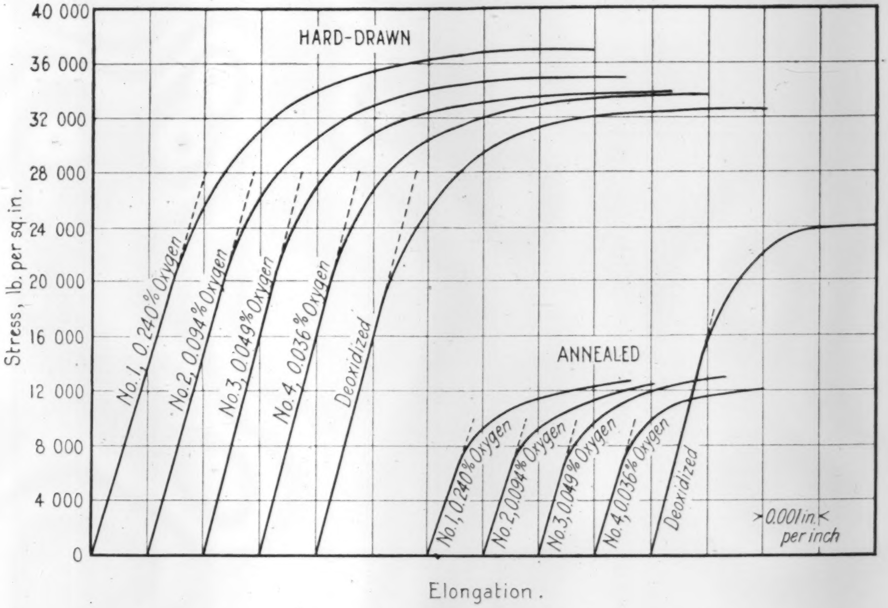

FIG. 18.—Stress-Strain Curves for Hard-Drawn Copper Containing Various Percentages of Oxygen.

Static tests were also made on annealed specimens of all the brasses and coppers and endurance specimens were prepared, but since few endurance tests on these specimens have yet been made, the data are omitted.

ENDURANCE PROPERTIES OF BRASS AND COPPER

For the preliminary endurance tests it was decided to run to 50 million cycles and then to raise the stress, if unbroken, the expectation being to run tests later at one stress to as many million cycles as might be required. Changes in the plans for the Bureau of Mines research work on alloys since this work was started make it unlikely

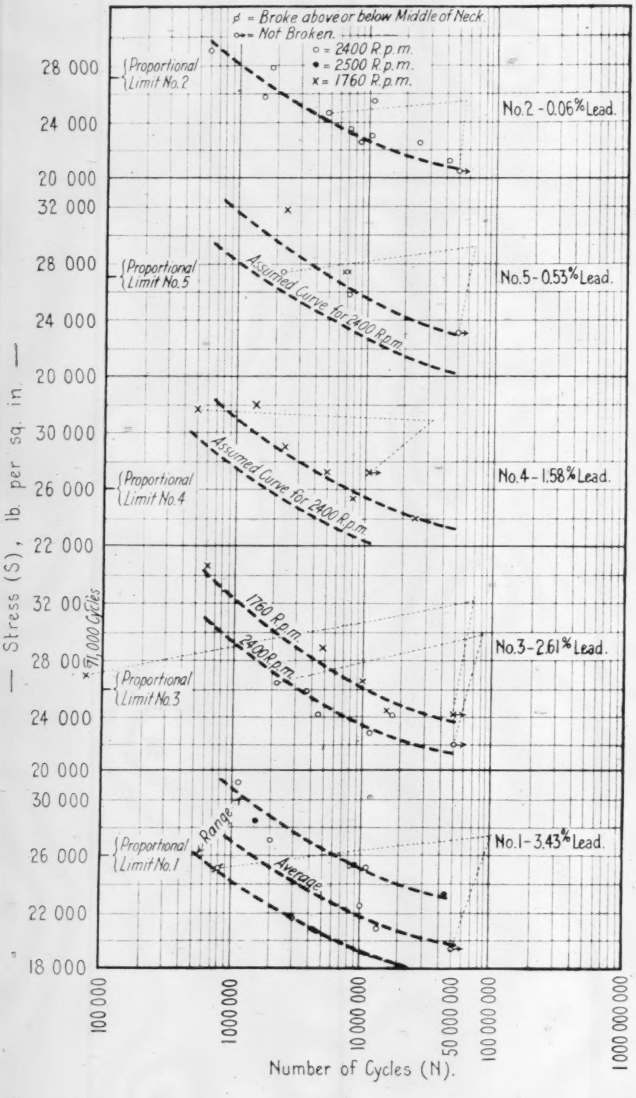

FIG. 19.—Rotary Bending Tests on Necked Specimens of Hard-Drawn Brass Containing Various Percentages of Lead. Copper-Zinc Ratio: 61.75 — 38.25.

that the program can be completed. It is therefore desirable to report on these admittedly preliminary tests for what they may show.

The results are shown in Figs. 19 and 20. In these figures a cross denotes a test at 1760 r. p. m. and a dot one at 2400 r. p. m., while a circle denotes a test at 2400 r. p. m. with the testing machine in somewhat better dynamic balance. As before, a line through a point denotes that the specimen did not break at the point of minimum section; an arrow denotes an unbroken specimen, and points for tests at a higher stress than the initial one are connected to the first point by converging lines. The position of the approximate proportional limit is also shown.

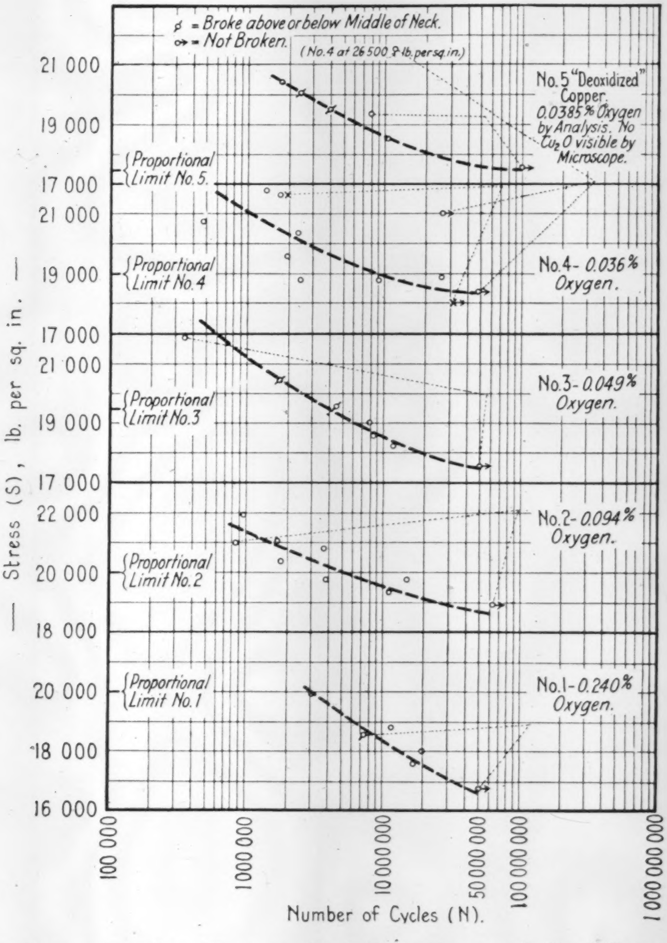

FIG. 20.—Rotary Bending Tests on Necked Specimens of Hard-Drawn Copper Containing Various Percentages of Oxygen.

Most of the tests on the brasses of 0.53, 1.58, and 2.61 per cent lead content were made with the machines in less perfect balance and may not be comparable to later tests, since the latter seem to average lower than the former where comparisons are possible (Fig. 19). The brass lowest in lead does not show up clearly to be any better in endurance than the one highest in lead. The "scatter" of the points is greater on the highly leaded material, but it is also rather wide on the material lowest in lead. The specimens unbroken after 50 million cycles and then tested at a higher stress show no strengthening, which we take to be an indication that no endurance limit has been reached. The *S*-log *N* plot is but very slightly curved, and the evidence shows that tests would have to be carried to many more than 50 million cycles to show whether or not an endurance limit exists. These brasses will fail under repetitions of stress well below the static proportional limit. The presence of lead reduces static ductility, but does not materially alter the tensile strength or proportional limit, and so far as our tests have gone, it does not materially affect the endurance properties. It seems reasonable to conclude that a sufficient number of specimens of all the samples would probably show approximately the same "scatter" about practically the same average curve.

The copper specimens (Fig. 20) show less "scatter" than the brass specimens and the curvature of the plot, although again very slight, is somewhat more marked in the two lots lowest in oxygen. One specimen of No. 4 (0.038 per cent oxygen) definitely shows strengthening. The stress for a life of 50 million cycles is only slightly below the static proportional limit in the specimens of lowest oxygen content and varies only from about 17,500 to about 18,500 lb. per sq. in. with variation in oxygen up to 0.094 per cent oxygen, although the static proportional limit rises with increase in oxygen. In the sample with 0.24 per cent oxygen (which also contains more sulfur than the others), the stress for a life of 50 million cycles drops to less than the value for the lower oxygen specimens, though the static strength still rises and the proportional limit is the same as with 0.094 per cent oxygen.

Except for the evidence of one specimen, there is nothing to show that hard-drawn copper has any real endurance limit, but the indications point more strongly in that direction than in the case of the brasses.

The endurance values, with the sole exception of that for the copper highest in oxygen, lie within a range approximately equal in percentage to the range of differences in tensile strength. The endurance value for the copper at 50 million cycles, with the one exception, is approximately one-half of the tensile strength, and for the brass, approximately one-third. Changes in proportional limit or in ductility exert no clear effect on the endurance. The very soft inhomogeneity, lead, in the relatively soft brass shows no clear indication of any local "stress-raising" effect, and the eutectic of the hard cuprous oxide with copper in a relatively soft copper matrix causes no marked reduction of endurance properties up to any oxygen content likely to be found in commercial copper. When the specimen contains more eutectic than copper, the endurance properties fall off slightly.

GENERAL CONCLUSIONS

The material which will withstand the highest stress in repeated loading appears to be a heat-treated alloy steel drawn for a very long time, at as high a temperature as is compatible with retention of high strength, in order to release internal stress. The steel should be clean—free from inclusions—and its surface should be free from scratches or tool marks crossing the line of applied stress. The piece should be made with generous fillets at changes of section. All these requirements look toward avoidance of local excess stress.

SUMMARY

1. The necessity for proper necking of endurance test pieces is shown, test pieces suitable for use on the Upton-Lewis machine are illustrated, and slight modifications of the machine are described.

2. The Upton-Lewis reversed bending endurance testing machine, properly used, gives results agreeing with those of the Sondericker type machine.

3. Specimens used should be free from transverse scratches.

4. The strengthening effect of understressing has been noted.

5. Transverse specimens give lower endurance results than longitudinal ones.

6. The type of S-log N curve described by McAdam appears to fit endurance test data better than that used by Moore.

7. The "knee" in the curve appears at a lower number of cycles in hard steels than in softer ones.

8. Endurance testing of steel can be accelerated by running only to one million or a few million cycles and then continuing the test at higher stress.

9. The rise-of-temperature method failed to give useful results on necked round specimens in reversed bending. Accelerated tests fail to show the presence of local "stress-raisers."

10. The curve obtained by plotting tensile strength against endurance limit is not a straight line through its whole length.

11. Internal stress due to quenching reduces the endurance limit of steel drawn at too low temperatures.

12. Increasing the draw temperature or the time of drawing so as to give fuller release of internal stress, raises the endurance limit.

13. Other things being equal, steels containing vanadium, molybdenum or nickel do not show material variation in the relation of endurance limit to tensile strength from that shown by comparable steels without those elements. Claims for favorable influence of these elements on endurance appear to have been exaggerated.

14. No relationship was found between endurance limit and either single or repeated blow impact tests.

15. Dirty steel is unreliable under repeated stress.

16. The shape and orientation of the inclusions in respect to the direction of applied repeated stress, is important.

17. The injurious effect of inclusions seems to be greater in hard steel than in soft steel.

18. Preliminary study of inhomogeneities such as lead in brass and oxygen in copper shows no marked effect on the endurance properties (up to 50 million cycles) in these softer materials.

19. In hard-drawn brass and copper no endurance limit has been definitely detected by tests to 50 million cycles.

20. Endurance results are given on 140 different heat treatments or conditions of 45 different steels, and on 10 lots of brass and copper.

REFERENCES

(1) H. F. Moore and J. B. Kommers, "An Investigation of the Fatigue of Metals" (contains bibliography on endurance), *Bulletin No. 124*, Engineering Experiment Station, University of Illinois (1921).

(2) H. F. Moore and T. M. Jasper, "An Investigation of the Fatigue of Metals," series of 1922. *Bulletin No. 136*, Engineering Experiment Station, University of Illinois (1923).

(3) H. F. Moore and T. M. Jasper, "An Investigation of the Fatigue of Metals," series of 1923. *Bulletin No. 142*, Engineering Experiment Station, University of Illinois (1924).

(4) H. F. Moore and W. J. Putnam, "Effect of Cold-Working and Rest on Resistance of Steel to Fatigue," *Bulletin No. 146*, Am. Inst. Mining and Metallurgical Engrs., p. 391 (1919).

(5) H. F. Moore and A. G. Gehrig, "Some Fatigue Tests on Nickle and Chrome-Nickle Steel,". *Proceedings*, Am. Soc. Testing Mats., Vol. XIX, Part II, p. 208 (1919)

(6) H. F. Moore, J. B. Kommers and T. M. Jasper, "Fatigue or Progressive Failure of Steel under Repeated Stress," *Proceedings*, Am. Soc. Testing Mats., Vol. 22, Part II, p. 266 (1922).

(7) D. J. McAdam, "Endurance of Steel under Repeated Stress." *Chemical and Metallurgical Engineering*, Vol. 25, p. 1081 (1921).

(8) D. J. McAdam, Discussion, *Proceedings*, Am. Soc. Testing Mats., Vol. 22, Part II, p. 288 (1922).

(9) D. J. McAdam, "Endurance Properties of Steel." *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 56 (1923).

(10) O. H. Basquin, "The Exponential Law of Endurance Tests." *Proceedings*, Am. Soc. Testing Mats., Vol. 10, p. 625 (1910).

(11) R. E. Lewton, "Some Endurance Tests of Spring Steels," *Transactions*, Am. Soc. Steel Treating, Vol. 3, p. 944 (1923).

(12) R. Stribeck, "Dauerfestigheit von Eisen und Stahl bei Wechselender Biegung," *Zeitschrift*, Ver. deutsche Ingenieure, Vol. 67, p. 631 (1923).

(13) D. J. McAdam, "Endurance and Impact Tests of Metals," *Proceedings*, Am. Soc. Testing Mats., Vol. 16, Part II, p. 296 (1916).

(14) F. C. Lea, "The Effect of Repetition Stresses on Materials." *Engineering* (London), Vol. 115, pp. 217, 252 (1923).

(15) C. F. Jenkin, "Fatigue in Metals," *Chemical and Metallurgical Engineering*, Vol. 28, p. 815 (1923).

(16) C. F. Jenkin, "Fatigue Failure in Metals," *Proceedings*, Royal Society (London), Series A, Vol. 103, p. 121 (1923).

(17) W. Rosenhain, S. L. Archbutt and S. A. E. Wells, "Production and Heat Treatment of an Aluminum Alloy," *Journal* (British Institute of Metals), Vol. 29, p. 206 (1923).

(18) W. Rosenhain, "Strain and Fracture in Metals," *Chemical and Metallurgical Engineering*, Vol. 28, p. 1030 (1923).

(19) J. H. Smith, "Some Experiments on Fatigue of Metals," *Journal*, Iron and Steel Inst. (British), p. 280 (1910); also R. G. Batson and J. H. Hyle, "Mechanical Testing," p. 55 (1922).

(20) L. Fraichet, "Essai Magnétique des Aciers a la Traction, Limites Elastiques," *Revue de Metallurgie*, Vol. 20, p. 560 (1923).

(21) W. J. Francke, "An Apparatus for Delicate Flexure Tests," *Proceedings*, Am. Soc. Testing Mats., Vol. 20, Part II, p. 372 (1920).

(22) C. E. Stromeyer, "Determination of Fatigue Limits under Alternating Stress Conditions," *Proceedings*, Royal Society (London), Series A, Vol. 90, p. 114 (1914).

(23) L. Bairstow, "The Fatigue of Metals," *Beama*, Vol. 11, p. 817 (1922); also, R. G. Batson and J. H. Hyle, "Mechanical Testing," p. 55 (1922).

(24) H. J. Gough, "Improvements in Methods of Fatigue Testing," *Engineering* (London), Vol. 132, p. 159 (1921).

(25) R. L. Templin, private communication, March 22, 1923.

(26) C. F. Jenkin, "Report on Materials of Construction Used in Aircraft and Aircraft Engines," British Aëronautical Research Committee, p. 8 (1920).

(29) T. Robson, "Determination of the Fatigue-Resisting Capacity of Steel under Alternating Stress," *Engineering* (London), Vol. 115, p. 67 (1923).

(28) R. L. Templin, "Non-Ferrous Metal Fatigue," *Iron Age*, Vol. 110, p. 356 (1922).

(29) H. J. Gough, "Elastic Limits of Copper under Cyclic Stress Variations," *Engineering* (London), Vol. 114, p. 291 (1922).

(30) L. Aitchison, "Engineering Steels," p. 209 (1921).

(31) L. Aitchison, "The Low Apparent Elastic Limit of Quenched or Work-Hardened Steels, *Carnegie Scholarship Memoirs*, Iron and Steel Inst., (British), Vol. 12, p. 113 (1923).

(32) L. Aitchison, "Materials in Aircraft Construction," *Engineering* (London), Vol. 117, p. 89 (1924).

(33) W. H. Hatfield, "Steel from the Standpoint of Marine Engineering," *Journal*, West of Scotland Iron and Steel Inst., Vol. 23, p. 52 (1921).

(34) W. H. Hatfield, "Further Notes on Automobile Steels" (contains bibliography on endurance), *Proceedings*, Inst. Automotive Engrs. (British), Vol. 15, p. 465 (1921).

(35) S. Whyte, Discussion, *Proceedings*, Inst. Automotive Engrs. (British), Vol. 15, p. 502 (1921).

(36) J. A. Mathews, "Present and Future of Alloy Steels," *Booklet*, Halcomb Steel Co.

(37) J. A. Mathews, Discussion, *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. 62, p. 476 (1920).

(38) S. L. Hoyt, "Static, Dynamic and Notch Toughness," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. 62, p. 476 (1920).

(39) R. P. Haigh, "Elastic and Fatigue Limits in Metals," *Metal Industry* (London), Vol. 21, p. 466 (1922).

(40) C. Frémont, "Alternating Stresses," *Comptes Rendus*, Vol. 168, p. 348 (1919); *Journal*, Inst. of Metals (British), Vol. 21, p. 469 (1919).

(41) W. Rosenhain, "Introduction to Physical Metallurgy," p. 318 (1914).

(42) H. M. Howe, "Metallography of Steel and Cast Iron," pp. 589, 591 (1916).

(43) F. J. Griffiths and D. M. Blacet, *U. S. Patent*, 1,471,655, October 23, 1923.

(44) F. L. Antisell, "Relation of Physical and Chemical Properties of Copper," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. 64, p. 432 (1921).

(45) D. Hanson, C. Marryat and G. W. Ford, "Investigation of the Effects of Impurities on Copper," Part I. "The Effects of Oxygen on Copper," *Journal*, Inst. of Metals (British), Vol. 30, p. 197 (1923).

(46) B. P. Haigh, "Experiments on the Fatigue of Brasses, "*Journal*, Inst. of Metals (British), Vol. 18, p. 55 (1917).

(47) R. R. Moore, "Resistance of Manganese Bronze, Duralumin and Electron Metal to Alternating Stresses," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, p. 106 (1923).

(48) "Effect of Sulfur on Endurance Properties of Rivet Steel," Third Preliminary Report of the Joint Committee on Investigation of Phosphorus and Sulfur in Steel, *Proceedings*, Am. Soc. Testing Mats, (Preprint to be presented at 1924 Annual Meeting).

(49) J. M. Lessells, "Notes on the Fatigue of Metals," *Mechanical Engineering*, Vol. 45, p. 695 (1923).

(50) J. M. Lessells, "Static and Dynamic Tests for Steel," *Transactions*, Am. Soc. Steel Treating, Vol. 4, p. 536 (1923).

(51) J. M. Lessells, "Carbon and Carbon-Vanadium Steel Castings—A Comparison," *Transactions*, Am. Soc. Steel Treating, Vol. 5, p. 144 (1924).

(52) H. J. Gough and D. Hanson, "The Behavior of Metals Subjected to Repeated Stresses," *Proceedings*, Royal Society (London), Series A, Vol. 104, p. 538 (1923); *Chemical Abstracts*, Vol. 18, p. 516 (1924).

(53) L. B. Tuckerman, "The Annual Report of Director of the Bureau of Standards for Fiscal Year ended June 30, 1923," p. 211.

(54) G. A. Hankins, "Properties of Nickel in Fatigue," British Aëronautical Research Committee, *Reports and Memorandums*, *No. 789*, November, 1921.

[For a discussion on Fatigue of Metals, see page 601.—ED.]

RESISTANCE OF METALS TO REPEATED STATIC AND IMPACT STRESSES

By R. R. Moore[1]

A paper read at the last annual meeting of this Society[2] gave the results of an investigation carried out by the Engineering Division of the U. S. Air Service to determine the effect of alternating stresses on the life of some non-ferrous metals. Due to the rapid development of light alloys for airplane and engine parts, it was necessary to extend this work to obtain sufficient information for efficient design and construction. It has been necessary also to investigate some of the heavy non-ferrous metals and some certain ferrous metals. In addition, tests have been made to determine the effect of a notch on the life of metals and also the resistance of metals to repeated impact stresses. The present paper describes the results of these tests which were made in the Physical Testing Laboratory of the Engineering Division at McCook Field, Dayton, Ohio.

Material

The metals tested are briefly as follows: four extruded magnesium-base aluminum alloys, and one extruded magnesium-base copper alloy; one extruded 10-per cent aluminum bronze heat treated; one cast 10-per-cent aluminum bronze with and without heat treatment; one cast manganese bronze; a 1050 steel; a carbon-vanadium steel with two heat treatments; and stainless iron. The details of chemical composition and heat treatment are given in Table I.

The magnesium-base alloys were extruded into $\frac{3}{4}$-in. diameter rods from chilled ingots $2\frac{15}{16}$ in. in diameter by 6 in. long which were pre-heated to 350 to 400° F. before extruding.

The extruded aluminum bronze specimens were taken from bars which were extruded at $1\frac{9}{32}$-in. diameter and drawn to $1\frac{1}{4}$-in. diameter.

The cast aluminum bronze and manganese bronze test bars were cast and heat treated in the McCook Field Foundry and Metallurgical Laboratory. The method of casting the bronze test bars has been previously described in detail.[2]

The 1050 steel specimens were taken from a $1\frac{1}{2}$-in. hot-rolled bar.

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[2] R. R. Moore, "Resistance of Manganese Bronze, Duralumin, and Electron Metal to Alternating Stresses," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 106 (1923).

The vanadium steel specimens were taken from a ¾-in. diameter hot-rolled bar.

The stainless iron specimens were taken from a 3-in. diameter hot-rolled bar.

In order to record the structure of the different alloys, micrographs were taken and are shown in Figs. 1, 2, and 3.

The micrograph of the cast 14-per-cent magnesium-copper alloy, shown in Fig. 1(*f*), is included to compare with the extruded metal in order to show the effect of the extruding on the grain structure of the magnesium-base alloys.

TABLE I.—CHEMICAL COMPOSITION AND HEAT TREATMENT.

All values are given in per cent.

	Material	Composition												
		Mg	Al	Cu	Mn	Zn	Fe	Si	Sn	C	V	Cr	P	S
No. 1	Mg-Al Alloy, Extruded	Rem.	4.29	....	....	....	0.03	....	....	....	....	....	....	....
No. 2	Mg-Al Alloy, Extruded	Rem.	4.40	....	0.26	....	0.03	....	....	....	....	....	....	....
No. 3	Mg-Al Alloy, Extruded	Rem.	6.70	....	....	....	0.04	....	....	....	....	....	....	....
No. 4	Mg-Al Alloy, Extruded	Rem.	6.80	....	0.26	....	0.04	....	....	....	....	....	....	....
No. 5	Mg-Cu Alloy, Extruded	Rem.	....	9.65	....	....	0.04	....	....	....	....	....	....	....
No. 6	Al Bronze, Extruded[a]	....	10.06	89.81	....	....	0.13	....	....	....	....	....	....	....
No. 7	Al Bronze, Cast	....	9.78	90.22	....	....	....	....	....	....	....	....	....	....
No. 8	Al Bronze, Heat Treated[b]	....	....	....	....	....	....	....	....	....	....	....	....	....
No. 9	Mn Bronze, Cast	....	0.23	56.85	0.20	Rem.	1.50	....	0.32	....	....	....	....	....
No. 10	1050 Steel[c]	....	....	....	0.74	....	....	....	....	0.55	....	....	0.010[d]	0.05
		....	....	....	0.74	....	....	....	....	0.59	0.16	0.12	0.010[d]	0.019
No. 11	Vanadium Steel, Heat Treatment No. 1[e]	....	....	....	....	....	....	....	....	....	....	....	....	....
No. 12	Vanadium Steel, Heat Treatment No. 2[f]	....	....	....	....	....	....	....	....	....	....	....	....	....
No. 13	Stainless Iron	....	....	....	....	....	....	....	....	0.03	0.27	13.47	0.010[d]	0.01

[a] Heat treated as follows: Quenched in water from 1650° F.; reheated to 1150° F. ½ hr.; cooled in furnace.

[b] Heat treated as follows: Quenched in water from 1650° F.; reheated to 1200° F. ½ hr.; cooled in furnace.

[c] Heat treatment as follows: Normalized 1600° F. 1 hr., air cooled; heated at 1550° F. ¾ hr., quenched in water, drawn at 1200° F. 1 hr.; furnace cooled to 900° F., then air cooled.

[d] Less than.

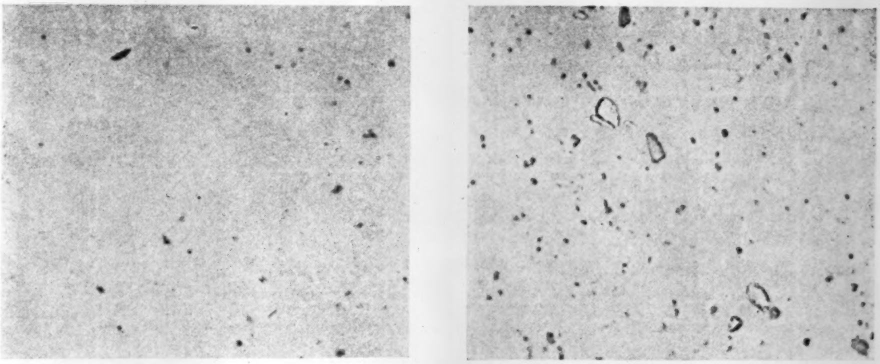
[e] Heated to 1600° F. 1 hr., cooled in air. Reheated to 1200° F. ½ hr., cooled in air. Reheated 1600° F. 2 hr., quenched in water. Reheated 1300° F. 1 hr., cooled in air.

[f] Heated to 1600° F. 1 hr., cooled in air. Reheated to 1200° F., held 1 hr. Cooled in air.

Micrographs of the bronzes are given in Fig. 2. The effect of heat treatment on the grain size and structure of the cast and extruded metals is clearly shown. It will be noticed from Table I that the cast and extruded aluminum bronzes are almost identical in chemical composition and heat treatment. The purpose of this was to make a comparison of the endurance limits of a cast and wrought metal.

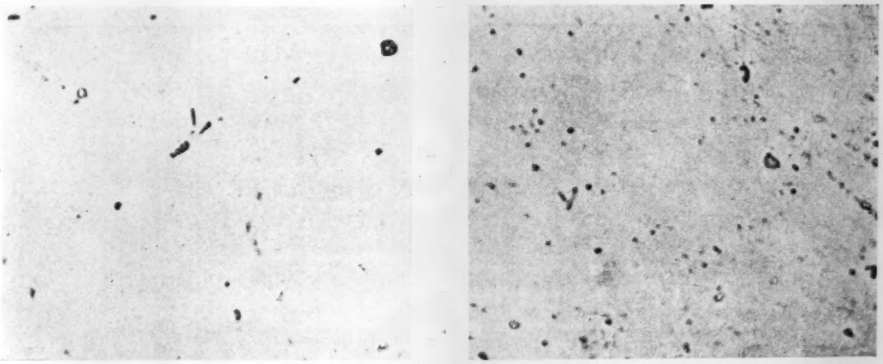
The banded structure of the vanadium steel is shown quite clearly in Fig. 3(*a*) while a higher magnification in Fig. 3(*b*) brings out the inclusions in the metal somewhat better.

The stainless iron of Fig. 3(*e*) shows large irregular ferrite grains which might indicate insufficient annealing. Traces of the original dendritic structure indicate incomplete hot working, which may be due in part to the size of the bar.



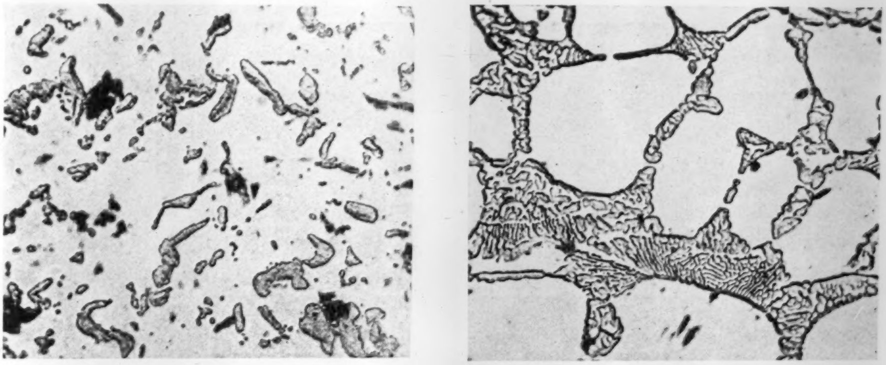
(*a*) 4 per cent Aluminum

(*b*) 6.5 per cent Aluminum



(*c*) 4 per cent Aluminum
0.25 per cent Manganese

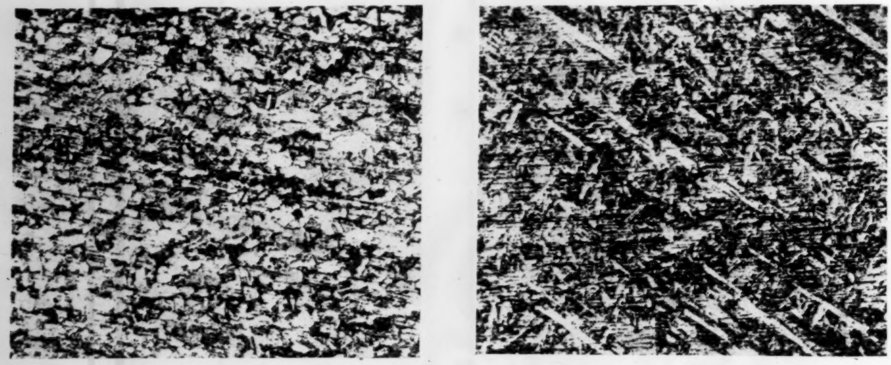
(*d*) 6.50 per cent Aluminum
0.25 per cent Manganese



(*e*) 9.65 per cent Copper

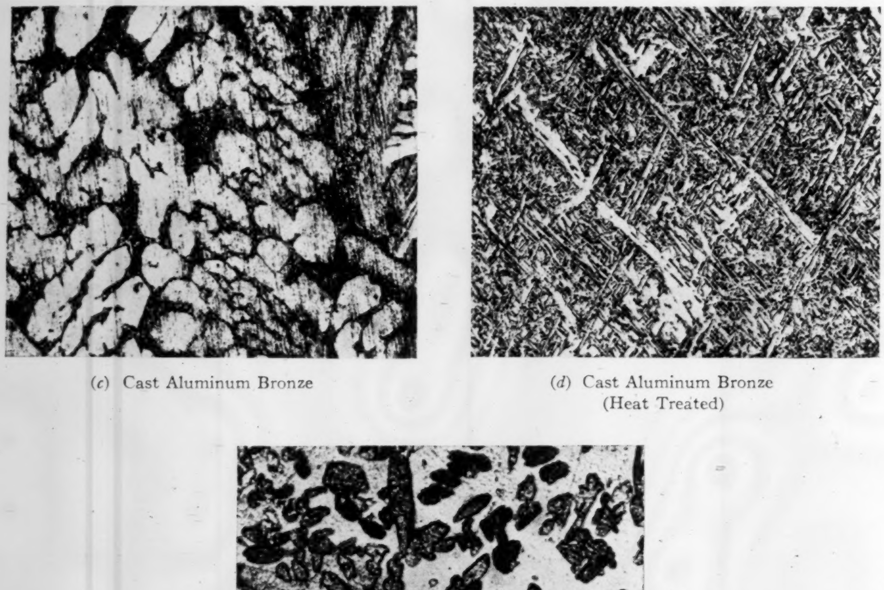
(*f*) Sand Cast 14.35 per cent Copper,
Remainder, Magnesium

FIG. 1.—Micrographs of Magnesium Alloys; Etching, None (× 500).



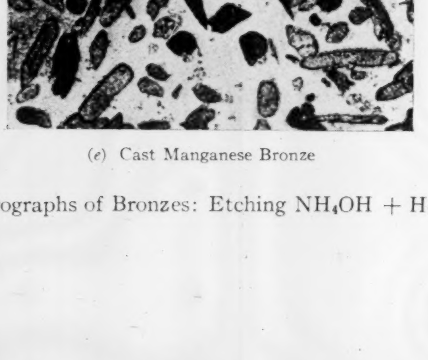
(*a*) Extruded Aluminum Bronze

(*b*) Extruded Aluminum Bronze (Heat Treated)



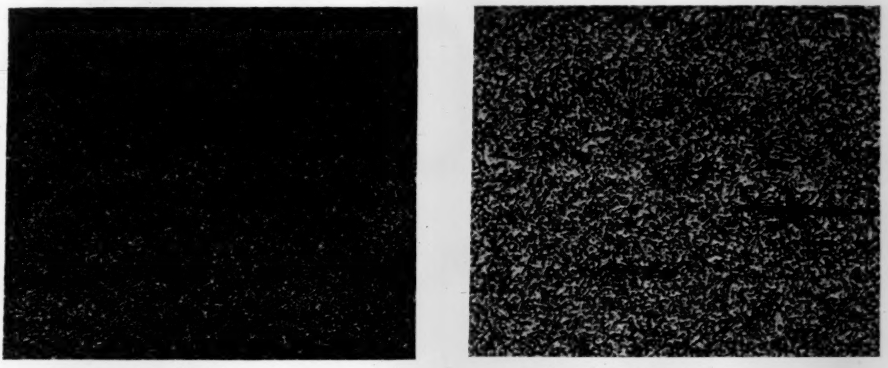
(*c*) Cast Aluminum Bronze

(*d*) Cast Aluminum Bronze (Heat Treated)



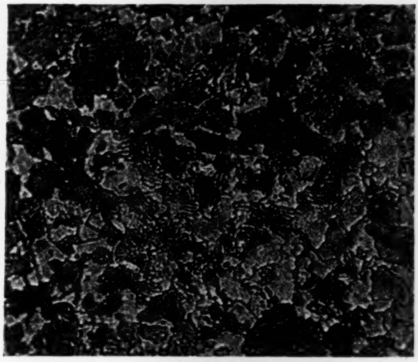
(*e*) Cast Manganese Bronze

FIG. 2.—Micrographs of Bronzes: Etching $NH_4OH + H_2O_2$ (× 100).

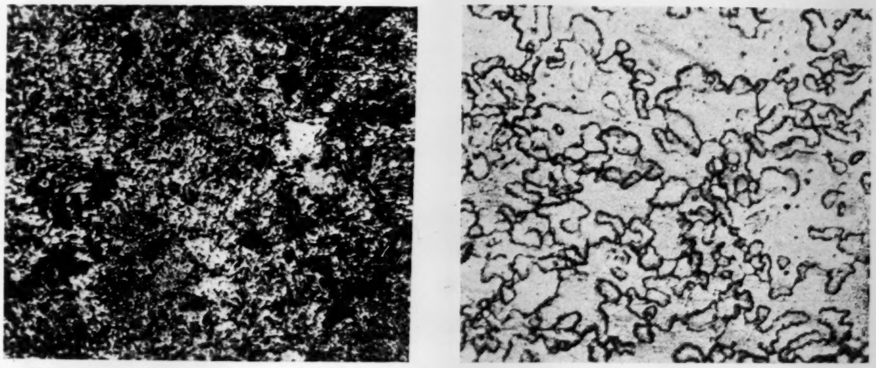


(*a*) Vanadium Steel (No. 11)
Etching, 5 NA for 5 seconds (X 100).

(*b*) Vanadium Steel (No. 11)
Etching, 5 NA for 5 seconds (X 500).



(*c*) Vanadium Steel (No. 12)
Etching, 3 per cent Alcoholic Nitric Acid (X 500).



(*d*) 1050 Steel
Etching, Alcoholic Picric Acid (X 500).

(*e*) Stainless Steel
Etching, Rosenhain's Chloride Reagent (X 100).

FIG. 3.—Micrographs of Ferrous Alloys.

GENERAL TESTS FOR PHYSICAL PROPERTIES

Tension, compression, torsion, shear, impact (Izod and Charpy notched bars), hardness (scleroscope, Rockwell, and Brinell), and specific gravity tests were made to classify the material and if possible develop a relation between any of these properties and the endurance limit.

Test Specimens.—Tension tests were made on ½-in. diameter, 8-in. gage length threaded-end specimen. Compression tests were made on a specimen of ⅝-in. gage diameter and 2-in. gage length with ends enlarged to ¾-in. Torsion tests were made on a specimen of ⅝-in. diameter with 10-in. gage length. Shear tests were made on a specimen of ½-in. diameter, 2 in. long. The tests were made in double shear. The Charpy test was made on a specimen 0.394 in. (10 mm.) square and 2.16 in. long with a notch 0.197 in. deep rounded to a 0.039-in. radius at the bottom.

TABLE II.—PHYSICAL PROPERTIES.

Number	Tension				Modulus of Elasticity, lb. per sq. in.	Compression			Torsion			Impact[a]		Hardness			Specific Gravity	Endurance Limit, lb. per sq. in.
	Proportional Limit, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent		Proportional Limit, lb. per sq. in.	Compressive Strength, lb. per sq. in.	Shear Strength, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Modulus of Rupture, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	Charpy, ft-lb.	Izod, ft-lb.	Brinell	Rockwell[b]	Scleroscope		
1	8 125	35 160	21.7	28.3	6 074 400	8 750	47 090	18 720	4 089	20 290	....	3.6	5.0	52	59	16	1.77	12 000
2	13 500	39 010	15.5	30.8	6 112 400	13 070	53 910	20 390	5 632	27 745	2 197 000	3.3	5.5	58	71	17	1.77	15 000
3	12 000	41 330	16.0	20.3	6 202 500	13 730	45 220	21 000	4 643	27 000	2 235 000	3.0	5.0	61	74	20	1.79	13 000
4	15 250	44 380	13.8	16.9	6 239 200	15 270	50 900	21 420	5 100	28 565	2 342 500	2.9	4.6	65	78	22	1.79	15 000
5	14 250	39 030	3.0	3.6	6 389 800	15 650	51 440	19 220	3 875	23 480	....	1.7	2.0	60	74	21	1.90	11 000
6	16 890	77 530	35.5	34.0	19 952 000	31 607	83 315	51 517	21 845	61 330	6 338 000	13.5	17.7	128	104	24	7.57	34 000
7	5 080	59 320	20.0	28.1	15 310 000	6 607	82 083	40 755	7 350	50 890	6 016 000	6.3	9.4	96	96	21	7.57	22 000
8	24 890	77 750	14.0	19.0	19 350 000	28 525	94 295	43 550	14 835	58 970	6 095 000	13.2	21.4	142	106	26	....	26 000
9	13 000	70 000	32.8	40.8	14 235 000	......	......	43 190	11 140	61 890	4 619 000	21.0	29.4	93	90	17	8.26	17 000
10	73 550	106 850	24.0	56.6	28 218 000	......	......	74 900	44 530	95 700	11 354 000	23.9	7.0	207	100	33	7.84	57 000
11	90 150	101 700	24.0	60.0	30 189 000	......	......	79 840	......	......	....	48.6	72.5	205	104	29	7.84	52 000
12	68 735	113 290	22.0	49.0	29 000 000	......	......	......	......	......	....	....	15.3	228	102	27	....	61 000
13	18 100	82 400	16.0	26.3	26 544 000	......	......	68 500	17 500	80 700	12 389 000	7.4	6.5	175	100	24	7.73	40 000

[a] Notched Bar. [b] Ball, ⅛in. diameter "B" Scale, 100 kg.

The Izod test was made on a specimen 0.394 in. (10 mm.) square with a striking distance of 0.866 in. The notch is a 45-deg. V 0.079 in. deep rounded to 0.01-in. radius.

Method of Test.—The proportional limits and moduli of elasticity in tension were obtained from stress-strain curves plotted from readings taken with a Ewing extensometer over an 8-in. gage length. The proportional limits in compression were obtained from stress-strain curves plotted from readings taken with a Berry strain gage in reverse action over a 2-in. gage length. The proportional limits and moduli of elasticity in torsion were obtained from curves plotted from readings taken with a torsion meter which read to 0.01 in. on an arc of 12-in. radius and over a 10-in. gage length. The proportional limit throughout this work is designated as the unit stress at which strain ceases to be proportional to the stress, and in every case was selected at the point of tangency of the straight line with the curve as near as practical.

Results of Tests.—The results of tests are given in Table II. The values in each case are the average of two tests with the exception of Charpy, Izod, and compression values which are the averages of four tests.

The values for the specific gravity of the magnesium-base alloys show that these alloys are very light, being only about 0.64 as heavy as duralumin. On a weight basis these alloys compare favorably with duralumin[1] in tensile strength, modulus of elasticity, compressive strength, and shear strength, but are slightly lower in proportional limits and are very much lower in notched bar value.

The tensile strengths of the heat-treated cast, and extruded aluminum bronzes are almost identical. The extruded metal, however, shows a lower proportional limit in tension than the cast metal, but higher proportional limits in compression and torsion, and also a higher shear strength and greater elongation. The notched bar values for both the wrought and cast metal are about the same. Any difference which may exist seems to be in favor of the cast metals, which is contrary to the usual conception of cast metals as being weaker than wrought metals under shock. This is especially interesting in consideration of the fact that they are almost identical in tensile strength and the elongation of the cast metal is only about one-half that of the wrought metal. Elongation evidently is no measure of shock resistance of grooved or notched parts.

The effect of heat treatment on the cast aluminum bronze is to raise all properties except elongation, which is lowered. The proportional limits of the aluminum bronze as cast are very low, in fact they are much lower than intended for this investigation. There is a possibility that these low values are to some extent the result of internal strains.

The cast manganese bronze shows better properties than the aluminum bronze as cast except for somewhat lower modulus values in tension and torsion. Attention is directed to the high notched-bar value, which is better than either the cast or extruded aluminum bronzes even after heat treatment.

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[1] R. R. Moore, "Resistance of Manganese Bronze, Duralumin, and Electron Metal to Alternating Stresses," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 106 (1923).

ALTERNATING-STRESS TESTS

TESTING MACHINES AND TEST SPECIMENS

The alternating stresses produced in the specimens under test were reversals of stress of equal magnitude from tension to compression. The stress is not evenly distributed over the cross-section of the test specimen but varies from zero at the center to a maximum at the outer surface. The endurance limits, therefore, are extreme fiber stresses.

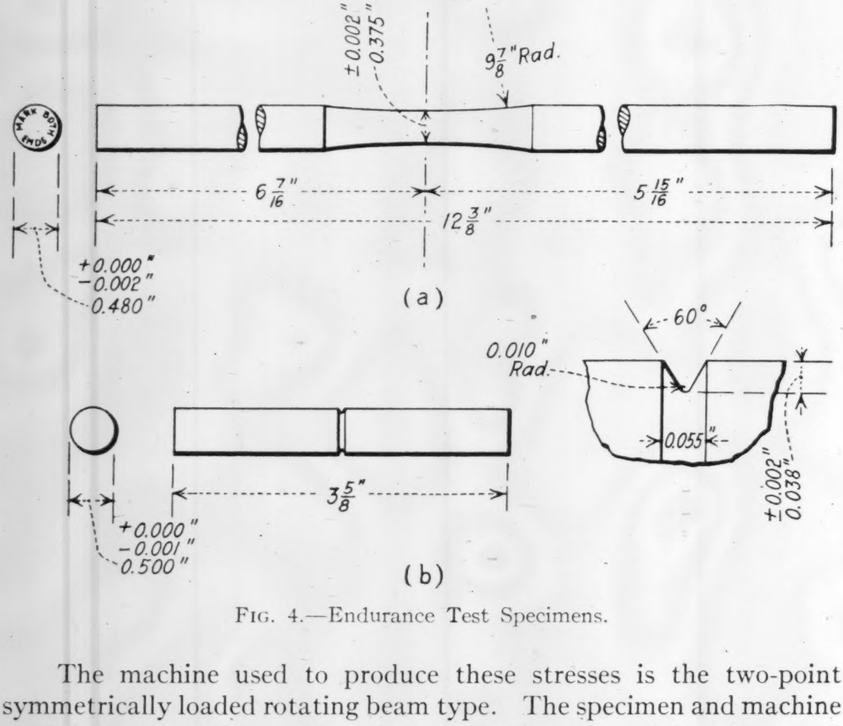
±0.002"
0.375"
$9\frac{7}{8}$" Rad.
MARK BOTH ENDS
$6\frac{7}{16}$"
$5\frac{15}{16}$"
$12\frac{3}{8}$"
+0.000"
−0.002"
0.480"
(a)
60°
0.010" Rad.
0.055"
±0.002"
0.038"
$3\frac{5}{8}$"
+0.000"
−0.001"
0.500"
(b)

FIG. 4.—Endurance Test Specimens.

The machine used to produce these stresses is the two-point symmetrically loaded rotating beam type. The specimen and machine used for testing the 1050 steel, vanadium steel, stainless iron, and manganese bronze have been previously described.[1] The aluminum bronze was tested on the same type of machine but the specimen used was somewhat larger in diameter in order to give greater stiffness to avoid bending during the machining, polishing, and setting up operations. This specimen is shown in Fig. 4(*a*).

The light alloy specimens (magnesium-aluminum and magnesium-

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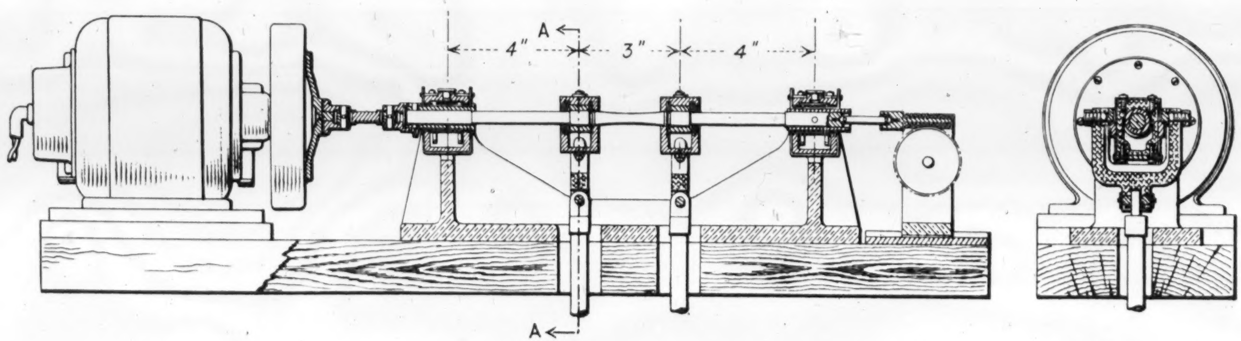
[1] *Loc. cit.*



Longitudinal Section.

Section A-A.

FIG. 5.—Rotating Beam Fatigue Machine for Light Alloys.

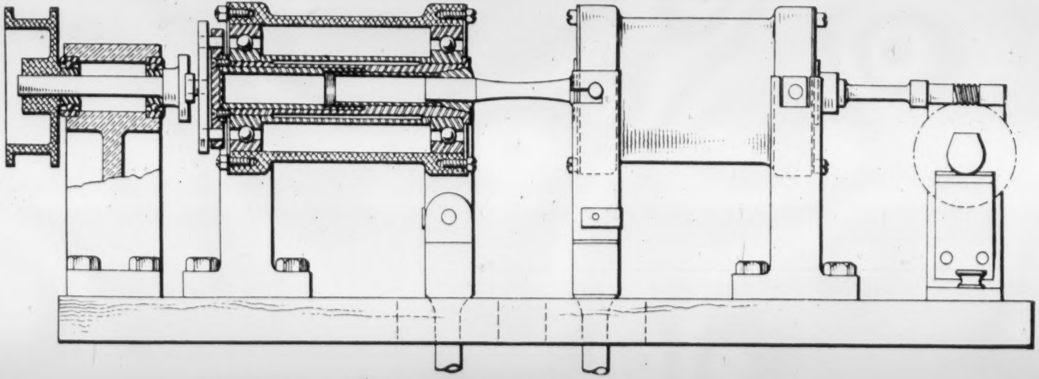


FIG. 6.—Rotating Beam Fatigue Machine, Short Specimen Type.

copper alloys) were tested in two different machines. The long-time tests were made with the same type of machine and specimens as used on the aluminum bronze. This type of machine and specimen are not entirely satisfactory for light alloy work as it is very difficult to avoid bending the specimen during the process of setting up the test. Furthermore, special care must be taken when starting the machine, for a sudden twist will injure the specimen if no means are provided to gradually obtain full speed. This machine was only used on the long-time tests where the time spent in setting up was only a small part of the total time of the test. The short-time tests were made on a machine built to overcome the difficulties of the old machines. This machine is shown in Fig. 5. The design and construction of this machine is in large part the work of Mr. H. Caminez of the Engine Design Branch of the Engineering Division. The main features are the light plain bearings, universal drive, and an automatic clutch for gradual starting. The plain bearings eliminate the noise and rattle of the ball bearings and are very light, thus permitting a larger live load to be applied through some shock absorbing medium. The universal drive insures no restraining of the beam action, a factor which must be considered in low stress work. The clutch, if properly designed, works remarkably well and entirely avoids jerking and twisting the soft specimens.

All test specimens were polished at the reduced section in order to eliminate tool marks and scratches. Polishing was done by applying to the rotating specimen several grades of Manning paper (in order No. 2, 1, 0, 00, 000) and No. 65 levigated alumina until no visible scratches remained. Micrographs of similar surface finishes have been previously given by the author.[1]

The speed of tests was 1500 r.p.m. on the ball bearing machines and 1800 r.p.m. on the plain bearing machine.

The tests on the notched specimens were made with a machine the same in principle as those described above, but so designed as to take a short specimen. The short specimen has the advantage of requiring less material and is easier to make, set up, and polish, due to greater stiffness. In addition, it is possible to obtain specimens cut across the direction of working, which is practically impossible with the long specimens. The machine used is shown in Fig. 6. This laboratory also has under development another type of such a machine which offers certain advantages when used on the light metals.

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[1] *Loc. cit.*

RESULTS OF TESTS

The results of the endurance tests are given in Figs. 7 to 9 which are plotted to semi-logarithmic coordinates. It is seen from these curves that the relation of stress to the number of repetitions of this stress which the material will withstand follows a straight line until a point is reached at which the specimen is capable of withstanding an extraordinarily large number of reversals of stress as compared to its life at the stress immediately above it. This point is the endurance limit of the material and is indicated by the sharp kink or "break" in the curve. The values of the endurance limits found from these curves are given in the last column of Table II. The relations of the endurance limits to other physical properties are given in Table III.

TABLE III.—RELATION OF ENDURANCE LIMIT TO OTHER PHYSICAL PROPERTIES.

	Material	Tension		Compression			Torsion		Impact		Hardness		
		Proportional Limit	Tensile Strength	Proportional Limit	Compressive Strength	Shear Strength	Proportional Limit	Modulus of Rupture	Charpy (×1000)	Izod (×1000)	Brinell (×1000)	Scleroscope (×1000)	Specific Gravity (×1000)
No. 1	Mg Base+4 per cent Al	1.48	0.343	1.38	0.253	0.632	2.94	0.591	3.33	2.40	0.231	0.75	6.78
No. 2	Mg Base+4 per cent Al+0.25 per cent Mn	1.11	0.385	1.15	0.278	0.736	2.66	0.541	4.55	2.73	0.259	0.88	8.48
No. 3	Mg Base+6.5 per cent Al	1.08	0.314	0.946	0.287	0.619	2.80	0.481	4.34	2.60	0.213	0.65	7.26
No. 4	Mg Base+6.5 per cent Al+0.25 per cent Mn	0.983	0.346	0.983	0.294	0.700	2.94	0.526	5.16	3.26	0.231	0.68	8.39
No. 5	Mg Base+10 per cent Cu	0.772	0.281	0.703	0.214	0.572	2.84	0.467	6.47	5.50	0.183	0.52	5.79
No. 6	Extruded Al Bronze, Heat treated	2.01	0.440	1.08	0.409	0.661	1.55	0.555	2.52	1.92	0.266	1.42	4.50
No. 7	Cast Al Bronze	4.33	0.371	3.33	0.268	0.540	3.00	0.432	3.50	2.34	0.229	1.05	2.90
No. 8	Cast *Al* Bronze, Heat Treated	1.04	0.335	0.913	0.276	0.597	1.75	0.441	1.97	1.21	0.183	1.00	3.44
No. 9	Manganese Bronze	1.307	0.243	.....	.....	0.394	1.525	0.275	0.81	0.577	0.183	1.00	2.06
No. 10	1050 Steel	0.775	0.533	.....	.....	0.761	1.28	0.596	2.38	8.14	0.275	1.73	7.27
No. 11	Vanadium Steel, Heat Treatment No. 1	0.577	0.511	.....	.....	0.652	.....	.....	1.07	0.717	0.254	1.79	6.63
No. 12	Vanadium Steel, Heat Treatment No. 2	0.887	0.538	.....	.....	.....	.....	.....	.....	3.99	0.267	2.26	7.77
No. 13	Stainless Iron	2.210	0.486	.....	.....	0.584	2.285	0.495	5.40	6.15	0.228	1.666	5.17

The difference in endurance limit between a 4-per-cent and 6.5-per-cent magnesium-aluminum alloy is seen to be very slight, only 1000 lb. per sq. in. in favor of the 6.5-per-cent alloy. The effect of adding 0.25 per cent manganese increases the endurance limit about 3000 lb. per sq. in. in the case of the 4-per-cent alloy and 2000 lb. per sq. in. in the 6.5-per-cent alloy. These increases, while numerically small, amount to 25 and 15.5 per cent, respectively, of their original values. It is to be noted here that the effect of manganese on the other physical properties is to give a greater percentage increase to the proportional limit values than to the ultimate strength values. There is also a drop in ductility, but this does not seem to affect the endurance limits. The copper alloy has a lower endurance limit than either of the aluminum alloys.

The results of tests by different investigators[1,2] indicate that the endurance limit is more closely related to the tensile strength than to any other physical property. The ratio of endurance limit to tensile strength is, therefore, best adapted to comparing the efficiency of the endurance properties of metals, and will be referred to as the endurance ratio. Numerous tests over a wide range of ferrous alloys indicate that the endurance ratio may vary from 0.35 to 0.68, the usual value being about 0.50.

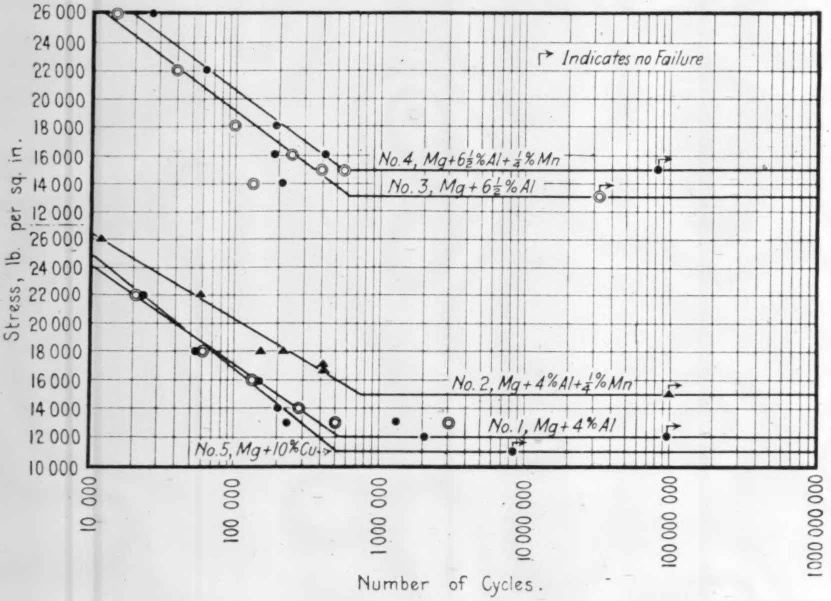

FIG. 7.—Endurance Curves for Light Alloys.

The light alloys studied in this investigation proved to have very low endurance ratios; as Table III shows, they lie between 0.261 and 0.385. On a weight basis, however, the magnesium-aluminum alloys are better than any of the other metals except the vanadium steel drawn at 1200° F. The magnesium-copper alloy on the other hand has the lowest endurance ratio of any of the metals tested with the exception of the cast manganese bronze. It is difficult to account for the low endurance limit of the copper alloy from the general physical properties because these properties are in most cases as good as for

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[1] Investigation of Fatigue of Metals, University of Illinois, *Bulletin No. 124*, by H. F. Moore and J. B. Kommers, and *Bulletin No. 136*, by H. F. Moore and T. M. Jasper.

[2] D. J. McAdam, Jr., "Endurance Properties of Steel: Their Relation to Other Physical Properties and to Chemical Composition," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 56 (1923).

the other alloys. The only difference is in the elongation and the notched bar values which are low. However, as previously stated, elongation did not affect the endurance limit of the aluminum alloy. H. F. Moore shows in *Bulletin No. 136*[1] that a 1.20-per-cent carbon steel heat treated so drastically as to reduce the elongation to 0.8 per cent and reduction of area to 2.4 per cent still has an endurance ratio of 0.48 which is as good as other steels in the same report which have an elongation of 25 per cent. McAdam[2] using the cantilever type of machine corroborates this with a 3-per-cent nickel 0.39-per-cent carbon steel which has an elongation of only 3 per cent and obtains an endurance ratio of 0.524. The failure of the copper alloy to come up to the aluminum alloy in endurance properties cannot be attributed at this time to low elongation.

A comparison of the endurance limits of the magnesium-base alloys and duralumin is interesting. As none of the tests in this paper have been run beyond 100,000,000 reversals of stress, the comparison will be made at the same point for duralumin. The author has given[3] an endurance curve for duralumin (as received) which indicates a stress of about 18,000 lb. sq. in. at 100,000,000 reversals. This is numerically greater than any of the magnesium-base alloys covered in this investigation. On a weight basis, however, the comparison is not so favorable, for duralumin shows a specific gravity ratio of 6.43 to be compared with the values for the light alloys given in the last column of Table III. Duralumin is here shown to be better than the 10-per-cent copper alloy but not quite so good as the others. The endurance ratio of duralumin is about 0.35, which is about the same as the magnesium alloys.

A comparison of the magnesium-aluminum alloys with a magnesium-zinc alloy known in the trade as electron metal, the endurance limit of which has been determined by the author,[3] shows that electron metal has a higher endurance limit (17,000 lb. per sq. in.) and $\frac{\text{Endurance Limit}}{\text{Specific Gravity} \times 1000}$ ratio (9.55) than any of these alloys. It is also better than these alloys in all other endurance property relations, and especially the proportional limit ratio, as electron metal has a much lower proportional limit.

The endurance curves for the bronzes are given in Fig. 8, and the endurance limits will be found in Table II. No results are given for aluminum bronze as extruded because the tests could not be completed in time due to the difficulty of obtaining a smooth running test. This trouble was caused by warping of the specimen after machining. Heat treating the specimens helped to remove this trouble as the internal strains due to the extruding process were considerably relieved.

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[1] *Loc. cit.* [2] *Loc. cit.* [3] *Loc. cit.*

The endurance limit of the extruded metal (heat treated) is seen to be about 32 per cent greater than that of the same metal in the cast condition (heat treated). As both the extruded and cast metal were of practically the same chemical composition and were treated to give the same tensile strength, this comparison is especially valuable in that it illustrates the relative endurance limits of a cast and a wrought metal. The author has been unable to find a similar comparison in the literature. It is not to be concluded, however, that the relation given here will hold for other alloys or even for the same alloy under different heat treatments.

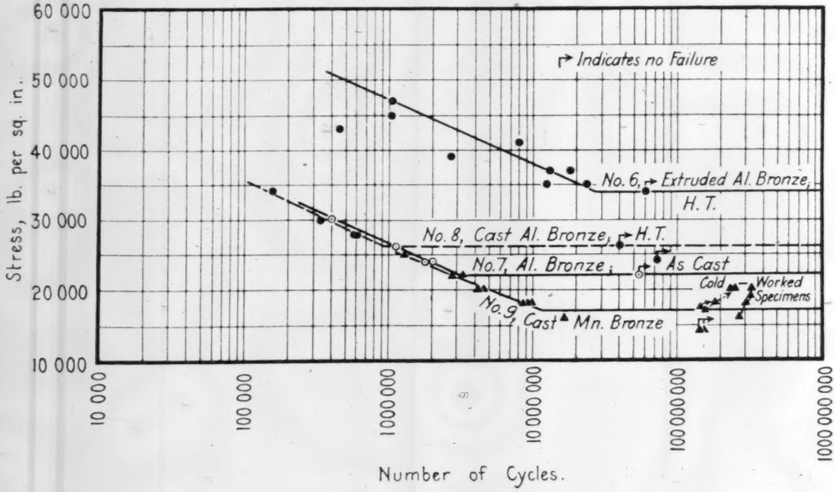

FIG. 8.—Endurance Tests on Bronzes.

Endurance tests on a 10-per-cent cast aluminum bronze heat treated and as cast have also been described by Corse and Comstock.[1] The investigators did not continue their tests to the point of obtaining an endurance limit as they have clearly stated. By plotting their results to semi-logarithmic coordinates the author has estimated that the endurance limit of the heat-treated metal would be about 28,000 lb. per sq. in. and of the metal as cast about 25,000 lb. per sq. in. These values compare favorably with the values of 26,000 and 22,000, respectively, which were obtained by the author. It is to be noted that their alloy showed somewhat higher tensile strength and considerably higher proportional limit, which may be accounted for by either the 0.91-per-cent iron content, or by the method of heat treatment, or both. Fig. 2(*d*) if compared with the structures shown by Corse and Comstock would indicate that the metal of Fig. 2(*d*) has been more rapidly cooled as interpreted from the sharpness of the acicular markings.

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[1] W. M. Corse and G. F. Comstock, "Aluminum Bronze: Some Recent Tests and Their Significance," *Proceedings*, Am. Soc. Testing Mats., Vol. XVI, Part II, p. 117 (1916).

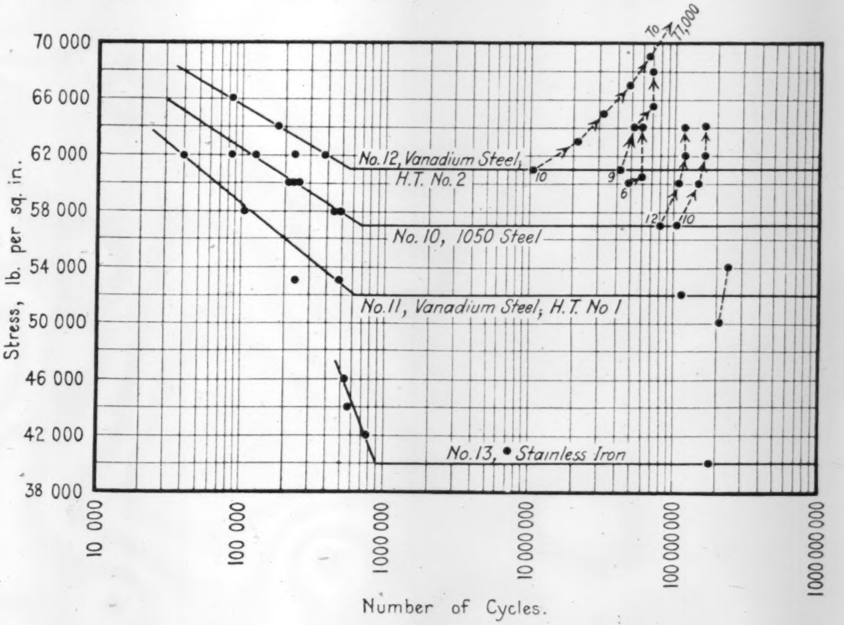

FIG. 9.—Endurance Tests on Ferrous Metals.

The endurance limit of the cast manganese bronze is about 23 per cent less than the aluminum bronze as cast. The endurance curves for both these alloys almost coincide. The aluminum bronze curve, however, breaks much sooner, giving a higher endurance limit. Corse and Comstock[1] also give an endurance curve for cast manganese bronze of similar chemical composition and physical properties. Their results if plotted to semi-logarithmic coordinates will be found to check extremely well with the curve in Fig. 8 and if their tests had been continued further it is reasonable to suppose that they would have obtained the same endurance limit. The curve in Fig. 8 shows that the author's tests have been run to 265,000,000 reversals of stress which seem sufficient to establish a practical endurance limit.

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[1] *Loc. cit.*

The values for the ratio of endurance limit to physical properties as given in Table III show that all the bronzes have very high ratios of endurance limit to proportional limit in tension. This ratio is especially high in the case of the aluminum bronze as cast. In this particular case, however, the proportional limit is below normal so that undue importance should not be given this high ratio value. It does show, however, that the endurance limit of these non-ferrous alloys is unaffected by the proportional limit as determined here.

The endurance curves for the ferrous metals are shown in Fig. 9 and the endurance limits as obtained from these curves are given in Table II. The carbon and vanadium steels were selected with similar carbon and manganese contents in order to determine the effect of vanadium on the endurance limit. It is evident that there is only a slight increase in the endurance ratio of the vanadium steel of heat treatment No. 2 over the plain carbon steel. The physical properties are about the same, the only difference being that the vanadium steel has a higher Izod value. This, however, does not account for the high endurance limit because the vanadium steel, heat treatment No. 1, which has an Izod value about five times as large as the other heat treatment and ten times as large as the plain carbon steel, has an endurance limit less than either. This particular heat treatment is evidently inducive to good Izod values. Furthermore, the vanadium steel, heat treatment No. 1, has the lowest endurance limit and endurance ratio in spite of the fact that it has a very high proportional limit as compared to its tensile strength. Summing up the results of these three sets of tests, we find a vanadium steel with a high Izod value and high proportional limit having an endurance limit and endurance ratio less than a plain carbon steel of the same carbon content, and also less than the same steel at a heat treatment giving a lower Izod value.

The stainless iron gives an endurance ratio of 0.486. This alloy is interesting because of its high ratio of endurance limit to proportional limit in tension. While it is not unusual to find an endurance limit greater than the proportional limit, as, for instance, the light alloys and the bronzes of this report, or as H. F. Moore[1] has found on some steels at different heat treatments, and in Armco iron in particular, the author does not know of any other ferrous alloy which has such a high ratio of endurance limit to proportional limit. This is further evidence that the endurance limit of ferrous alloys is independent of the proportional limit.

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[1] *Loc. cit.*

While making the endurance tests on the light alloys, the author was surprised to find that the break in the endurance curve occurred at a very low number (600,000 to 700,000) of reversals of stress as compared to the breaks of other light non-ferrous alloy curves which are usually quite high. Electron metal, a magnesium-zinc alloy previously tested by the author,[1] shows a break at about 28,000,000 reversals of stress. In Fig. 10 is shown the relation between endurance limit and number of reversals at break for some ferrous metals taken from H. F. Moore's work and also the alloys of the present investigation. Although Moore's curves were plotted to log-log coordinates, the break point is very near the same if plotted to semi-logarithmic coordinates. Considering only the ferrous metals it is evident that although there is some scatter of points there is a well-directed trend which would seem to indicate that the lower the endurance limit the greater the number of reversals at the break.

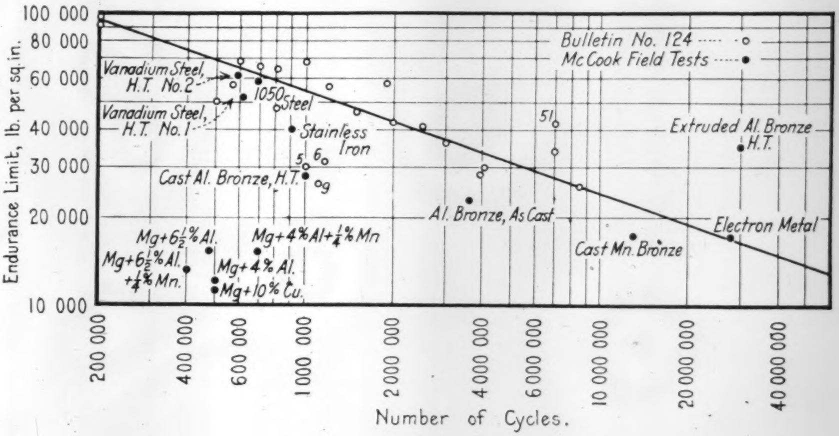

FIG. 10.—Relation of Reversals at "Break" to Endurance Limit.

Of the ferrous metals Nos. 6, 9, 50, 51 and the stainless iron show the greatest deviation from the curve. Attention is directed to the interesting fact that these particular metals have an endurance limit greater than their proportional limit. The non-ferrous metals, with the exception of the manganese bronze and electron metal, do not lie near the curve. This deviation is most marked in the whole group of magnesium-aluminum and magnesium-copper alloys. In fact, it would seem as if this group of alloys were of an entirely different character.

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[1] *Loc. cit.*

TABLE IV.—EFFECT OF COLD WORKING ON ENDURANCE LIMIT.

STRESS, LB. PER SQ. IN.	NUMBER OF REVERSALS		
	CAST MANGANESE BRONZE		
	SPECIMEN 2475-11	SPECIMEN 2475-7	SPECIMEN 2471-11
16 000	265 451 900	......	......
17 000	......	149 872 600	150 377 400
18 000	33 684 900	28 588 500	28 753 500
19 000	22 990 500	19 900 000	20 120 700
20 000	13 160 400 (Failed)	33 058 700 (Failed)	37 454 300 (Failed)
Increase in Endurance Limit, per cent	11.7	11.7	11.7
	1050 STEEL		
	SPECIMEN 10	SPECIMEN 12	
57 000	106 331 300	78 374 900	
60 000	41 600 500	30 883 000	
62 000	11 662 800	12 181 500	
64 000	123 800 (Failed)	95 700 (Failed)	
Increase in Endurance Limit, per cent	8.8	8.8	
	VANADIUM STEEL, HEAT TREATMENT NO. 2		
	SPECIMEN 10	SPECIMEN 9	SPECIMEN 6
60 000	......	......	47 692 200
61 000	10 605 200	42 240 700	10 369 400
63 000	11 279 800	......	......
64 000	......	15 980 000	2 636 300
65 000	11 279 200	......	(Did not fail,
67 000	15 829 400	......	test stopped)
68 000	......	387 400	......
69 000	9 706 600	(Failed)	......
71 000	11 017 300	......	......
73 000	11 552 000	......	......
75 000	13 272 100	......	......
77 000	9 465 000	......	......
80 000	444 600 (Failed)	......	......
Increase in Endurance Limit, per cent	26.2	5.9	4.7

In comparing the relation of the endurance limits of ferrous and non-ferrous metals to other physical properties, two points seem to stand out which are interesting but at the present time can only be expressed as broad generalities. It is more usual for the non-ferrous metals to have endurance limits greater than the proportional limits, while this is more unusual in ferrous metals. Secondly, the ratio of endurance limit to tensile strength (endurance ratio) is less in the non-ferrous metals than in the ferrous metals. Exceptions of course are found to both of these expressions.

EFFECT OF COLD WORKING

Several tests were made on each of the vanadium steels, plain carbon steel, and manganese bronze to determine if it were possible to raise the endurance limit by mildly cold working the specimen. The cold working was accomplished by increasing the stress in steps of 1000 or 2000 lb. per sq. in. as the specimen rotated.

The specimens used for these tests had already run a sufficient length of time to determine the endurance limit, so that the first stress applied was not above the endurance limit of the material. In some cases these first runs were very long, as, for instance, in the case of the manganese bronze. The length of run of each step was longer than that found at the break point of the endurance curve for the material, and, if the specimen did not fail, it was assumed that this stress was either at or below a new endurance limit for the material which had been developed by this process of cold working. The stress was increased as described until failure occurred, and the new endurance limit was taken at the highest stress which gave no failure.

The results of these tests are given in Table IV and are plotted on Figs. 8 and 9. The paths followed are indicated by the dotted lines. It is seen that the endurance limit of the 1050 steel was raised about 8 per cent and that of the vanadium steel about 5 per cent for specimens Nos. 6 and 9, and 26 per cent for specimen No. 10 which was loaded more gradually. The cast manganese bronze was raised about 11 per cent. These tests clearly indicate that it is quite possible to raise the endurance limit of a metal by cold work. Specimen No. 10 of the vanadium steel, which had an initial run of about 10,000,000 and was raised 2000 lb. per sq. in. about every 10,000,000 reversals, was raised much higher than those specimens which had long initial runs and some long intermediate runs. It is interesting to note that the cast manganese bronze specimens also responded to this treatment even after having been severely worked at the endurance limit. This would indicate that although cast manganese bronze shows a low endurance limit it may be possible to improve it by proper working. It may also be possible to extend this to other non-ferrous metals.

EFFECT OF NOTCHES

A sudden change in cross-section, such as a shoulder, groove, or notch, causes an increase of stress which is not usually provided for by the ordinary formulas of strength of materials. The amount of concentration or increase of stress depends primarily on the shape of the change in cross-section. C. E. Inglis[1] has shown mathematically that the stress at the bottom of the groove in the edge of a plate in tension is represented by the expression:

$$S_c = S_m \ (1 + 2 \sqrt{d/r})$$

where S_c is the actual stress at bottom of the groove,
S_m is the mean stress across the plate,
d is the depth of groove,
r is the radius of curvature at bottom of groove.

This relation holds only for stresses within the elastic limit, and when the groove near its ends merges into an ellipse. A rounded V notch fulfills this latter condition close enough so as to check quite well in the expression given.

E. G. Coker[2] has confirmed this relation experimentally by means of his optical stress method. A. A. Griffith[3] has extended the theory by means of his soap bubble method to twisted shafts containing V notch scratches rounded at the bottom. The following table[4] is given by Griffith and shows the increase of torsional stress at the root of scratches of various shapes:

RATIO OF INCREASE OF TORSIONAL STRESS AT ROOT OF SCRATCHES OF VARIOUS SHAPES

Angle of V, deg.	Ratio d/r				
	$\frac{1}{2}$	1	3	5	9
0	....	2.01	2.66	3.23	4.54
60	1.84	2.00	2.54	3.06	3.99
90	1.81	1.95	2.40	2.64	3.12
120	1.66	1.75	1.95	2.00	2.13

While these values only apply to torsional stresses, he has shown mathematically that the corresponding figures for tensile stresses in a shaft subject to a bending moment may be obtained by increasing the torsional figures in the ratio:

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[1] C. E. Inglis, "Stresses in a Plate Due to the Presence of Cracks and Sharp Corners," *Transactions*, Inst. Naval Architects, Part I (1913).

[2] E. G. Coker, *Proceedings*, Inst. Mechanical Engrs. (1913).

[3] A. A. Griffith, "Effect of Surface Scratches on the Strength of Shafts and Other Members," British Advisory Committee for Aëronautics, December, 1918.

[4] Taken from Report of Materials of Construction used in Aircraft and Aircraft Engines, by E. F. Jenkin.

$$\frac{1 + 2\sqrt{d/r}}{1 + \sqrt{d/r}}$$

With this data the actual stress at the bottom of a notch in a rotating beam fatigue specimen can be determined and some idea can be formed as to the effect of the concentrated stresses themselves on the endurance properties of metals.

The notch selected for these tests is the same as the notch used in the Stanton repeated impact tests to be described later. This notch is shown in Fig. 4 (*b*).

TABLE V.—EFFECT OF NOTCH ON THE ENDURANCE LIMIT OF METALS.

	Material	Endurance Limit of Material from Table II	Endurance Limit of Notched Specimen	Reduction of Endurance Limit, per cent
No. 1	Mg+4 per cent Aluminum	12 000	8 000	33
No. 2	Mg+4 per cent Al+0.25 Mn	15 000	10 000	33
No. 3	Mg+6.5 per cent Al	13 000	10 000	23
No. 5	Mg+10 per cent Copper	11 000	6 000	45
No. 6	Extruded Al Bronze, Heat Treated	34 000	20 000	41
No. 8	Cast Al Bronze, Heat Treated	26 000	22 000	15
No. 10	1050 Steel	57 000	24 000	58

By substituting the values of *d* and *r* as given in Fig. 4 (*b*) in the formula given by Ingliss we obtain: $1 + 2\sqrt{d/r} = 4.898$.

By interpolation, we obtain from Griffith's table the torsional value 2.75 for this type of notch. The factor $\frac{1 + 2\sqrt{d/r}}{1 + \sqrt{d/r}} = 1.661$. Following Griffith's method then, the actual stress at the bottom of this notch becomes 4.568 times the computed stress.

If we are to assume that the stress in the notched specimen must nowhere exceed the endurance limit of the material in order that the specimen shall not fail, due to repeated stresses, then according to Griffith's method the endurance limit of the notched specimen computed by the ordinary formulas using the diameter at the bottom of the notch may be expressed as follows:

$$\text{Endurance limit of notched specimen} = \frac{\text{Endurance Limit of Material}}{4.568} = 0.219 \text{ (endurance limit of material)}$$

or nearly 22 per cent. In other words, the endurance limit of the material has been reduced 78 per cent by the presence of this particular notch.

In order to determine whether this relation actually holds or whether other factors not readily apparent modify the results, actual endurance tests were made on specimens of the 1050 steel, four of the light alloys, and the extruded and cast aluminum bronze (both heat treated). The results of these tests are plotted in Fig. 11 and compared numerically in Table V. The greatest reduction in endurance limit was obtained on the 1050 steel and amounted to 58 per cent. The light alloys show a reduction of 23 to 45 per cent, the highest reduction being obtained on the magnesium-copper alloy. The extruded aluminum bronze showed a reduction of 41 per cent and the same metal cast showed a reduction of 15 per cent. The endurance limit of the cast metal evidently is not as greatly affected by the notch as the extruded metal, in fact its actual endurance limit when notched is at least as high if not higher than that of the extruded metal.

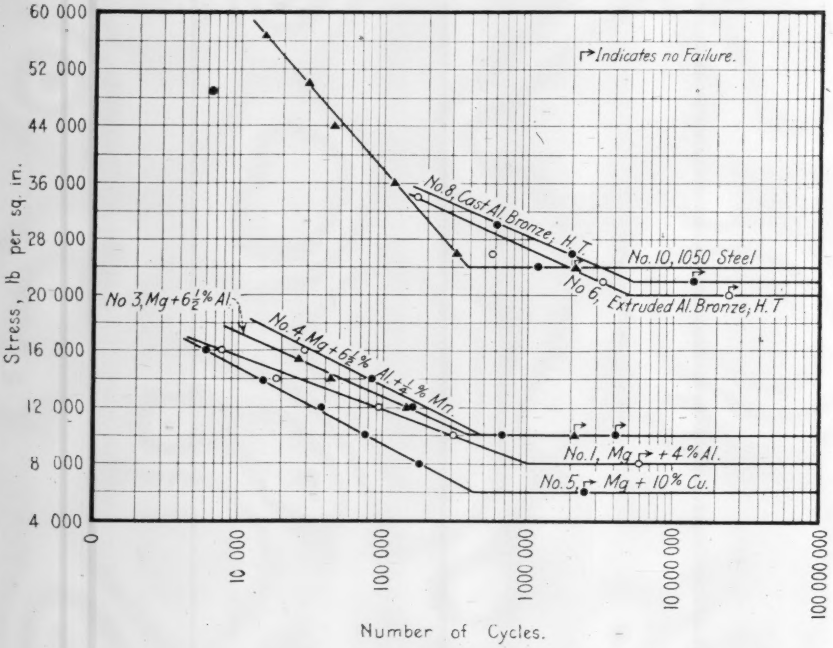

FIG. 11.—Endurance Tests on Notched Specimens.

These results are all much less than would be expected from the computations of stress distribution. This discrepancy has also been found by W. N. Thomas[1] who has investigated a number of sizes of notches. With a 0.33-per-cent carbon steel normalized, he obtains a reduction in endurance limit of about 53 per cent for a notch quite similar to the notch described here. This is a good check with the 58 per cent obtained on the 1050 steel. The main part of Thomas' research was confined to fine scratches (less than 0.0025 in. deep) for which he obtains reductions of endurance limit from 13 to 30 per cent.

It is evident from these tests that the effect of a notch on the endurance limit is not in proportion to the concentration of stress, but is considerably less depending on the material and the shape of the notch. The reason for this is not quite clear, but Griffith[2] having given considerable attention to the subject seems to be of the opinion that stress redistribution is partly responsible for this condition. Some recent tests by Gough and Hanson[3] indicate that there is definite permanent strain within the endurance limit which would seem to support the redistribution theory.

REPEATED IMPACT TESTS

Repeated impact tests were made on a Stanton type machine which applies a blow alternately to opposite sides of a notched specimen supported as a simple beam. A complete reversal of stress is thus obtained as in the case of the static endurance tests. The specimen is $\frac{1}{2}$ in. in diameter and notched at the center of the span where the blow is struck as shown in Fig. 4 (*b*). In the ordinary Stanton machine there is no provision for catching the rebound of the hammer after it strikes the specimen. An electrically operated catch was constructed to prevent this rebound for it was shown by some preliminary tests that the rebounding blow affects the life of the test specimen. The catch is pulled into position by an electromagnet timed from a disk type switch mounted on the driving pulley. In these tests no impact endurance limit was obtained because it was impractical to make the energy of blow small enough. The substitution of a light head on the hammer to reduce the energy of blow is not satisfactory, because the center of percussion is thrown off if the shank is not also remodeled. It would also be necessary to protect the specimen at the point of impact because it becomes considerably battered after a long run.

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[1] W. N. Thomas, "The Effect of Scratches and of Various Workshop Finishes upon the Fatigue Strength of Steel," Reports and Memoranda No. 860, Aëronautical Research Committee (British).

[2] A. A. Griffith, "Stress Concentration in Theory and Practice," British Assoc. for the Advancement of Science, 1921.

[3] H. J. Gough and D. Hanson, "Behavior of Metals Subjected to Repeated Stresses," *Proceedings*, Royal Soc., Vol. 104, 1923.

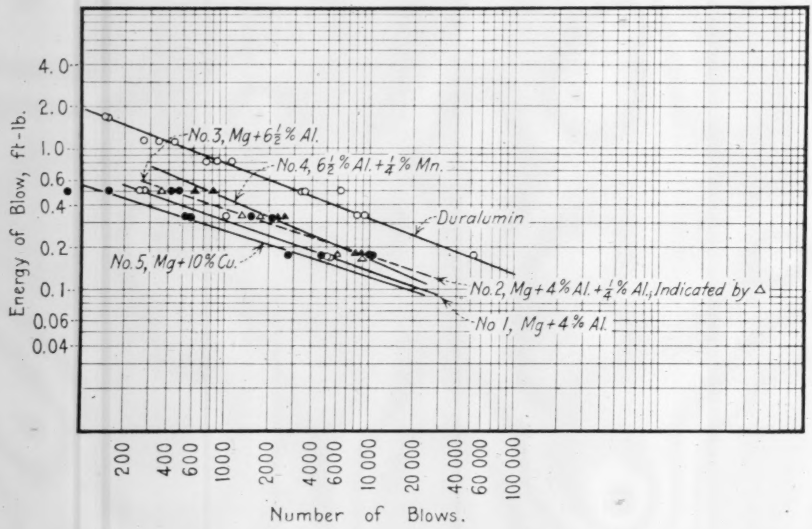

FIG. 12.—Repeated Impact on Light Alloys.

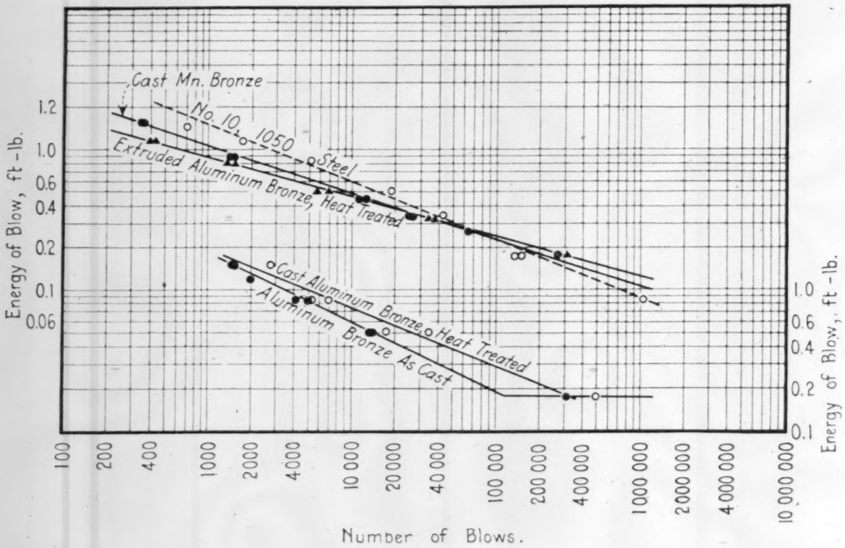

FIG. 13.—Repeated Impact on Steel and Bronze.

The results of the tests are shown in Figs. 12 and 13. From Fig. 12 it is clear that the magnesium-base alloys are not as good as the duralumin. The 6.5 per cent aluminum +0.25 per cent manganese alloy is better than the other magnesium-base alloys at the higher stresses but seems to be surpassed by the 4-per-cent alloy on the longer tests. The 10 per cent copper alloy is the poorest in so far as these tests have gone.

Fig. 13, which gives the results of the tests on the bronzes and the 1050 steel, indicates that there is not a great difference between the resistance of any of these alloys to repeated impact stresses. The cast aluminum bronze both heat treated and as cast appears better than the 1050 steel. The curve for the cast maganese bronze crosses above the 1050 steel curve at the low stresses. The extruded aluminum bronze is the poorest at the high stresses but the best at the low stresses. The comparatively poor showing of the 1050 steel is rather surprising when the tensile strength, elongation, and endurance limit are taken into consideration. This, however, may be due to the fact that this metal is more seriously affected by the concentration of stress at the bottom of the notch than the other metals as was shown by the notched specimen endurance tests. At the same time it should be noted that the heat-treated cast aluminum bronze was least affected by the notch and it showed the best resistance to the repeated blows.

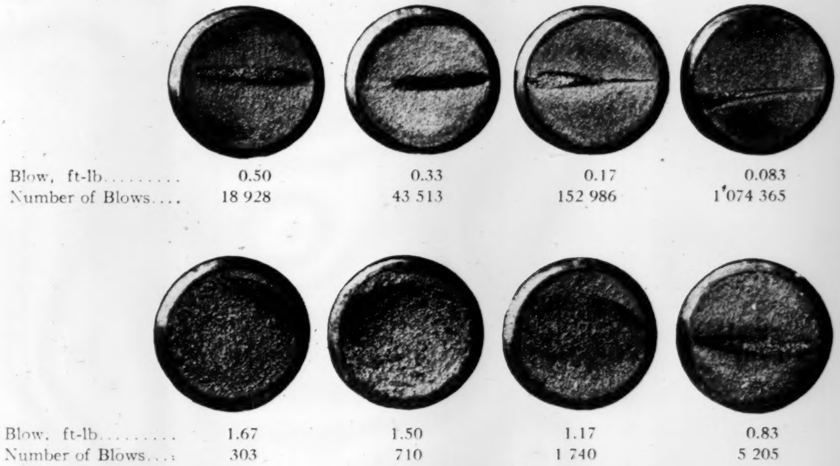

FIG. 14.—Effect of Number of Blows on Fracture of Stanton Impact Specimens of 1050 Steel.

It appears from these tests that the effect of sudden changes of section on the resistance of various metals to different types of stress cannot always be solved by an analysis of the stress concentration. The effect varies with the different metals. The previous comparisons have been drawn from tests which were not run to the point of obtaining the actual impact endurance limit, and should be judged accordingly.

D. J. McAdam[1] has pointed out that the repeated impact test measures the resistance to both impact and endurance properties depending on the length of the test. In the heavy blow test, the impact resisting properties are the main source of strength while in the light blow or long test the endurance properties resist failure. This is very nicely demonstrated by examining a series of fractures, as shown in Fig. 14, which are the test specimens of the 1050 steel. In the short test the fracture appears crystallin, covering almost the entire fractured surface. As the blow is made lighter and the test lengthens, the crystallin area becomes smaller and the fine grain area becomes larger. This crystallin fracture is characteristic of sudden failure (on this particular steel and heat treatment) and is still visible in the one million blow test indicating the location of the final parting of the metal, which is sudden. If the test is run at still lighter blows until the impact endurance limit is reached, it is likely that almost all traces of crystallinity will disappear and the fracture will be very much like that of a static fatigue failure. Evidences of this are already apparent in the million-blow test where the crystallin region is only a thin line which does not extend entirely across the face of the fracture.

These fractures are additional but probably unnecessary evidence against the old theory of failure by crystallization. The crystallin fracture is not the cause of sudden failure as wrongly interpreted in this theory but rather the result of sudden failure as clearly shown here.

It is evidently quite dangerous to attempt to judge the relative value of metals by a comparison of the number of blows they will withstand to fracture, at a fixed energy of blow, as it is doubtful what property is being measured. Furthermore, a comparison made at a certain energy of blow may be entirely reversed when made at a lower or higher energy because the curves for different metals may cross each other as shown.

Acknowledgment.—The writer wishes to acknowledge the valuable assistance of Messrs. S. W. Thompson, C. F. McMahon, and H. W. Boulton in the running of these tests, also Lieutenant A. J. Lyon under whose supervision the heat treating of the metals and the casting of the bronzes were done.

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[1] *Loc. cit.*

CONCLUSIONS

1. On a weight basis the endurance properties of the magnesium-aluminum alloys are about as good as duralumin, but not as good as electron metal. The magnesium-copper alloy does not show up as well as the magnesium-aluminum alloys.

2. The addition of 0.25 per cent of manganese to the magnesium-aluminum alloys raises the endurance limit about 15 to 25 per cent.

3. Extruded 10 per cent aluminum bronze has an endurance limit 32 per cent higher than the same metal cast. The endurance limit of manganese bronze as cast is about 23 per cent less than aluminum bronze as cast.

4. The endurance limits of both the ferrous and non-ferrous metals covered in this investigation are independent of proportional limit or elongation. The endurance limits of non-ferrous metals are usually greater than the proportional limit, while the reverse is more often true of the ferrous metals.

5. Vanadium does not appear to affect the endurance limit of a plain carbon steel.

6. The endurance limit of steels and manganese bronze can be raised by cold work. An increase of 8 per cent was obtained on a 1050 steel and a maximum of 26 per cent on a vanadium steel, depending on the method of working. An increase of 11 per cent was obtained on cast manganese bronze.

7. The effect of notches on the endurance properties of metal is not in proportion to the concentration of stress caused by the notches. The effect is much less than would be expected from the stress concentration. The maximum decrease in endurance limit found was 58 per cent, which was obtained on the 1050 steel. The magnesium alloys showed reductions of 23 to 45 per cent, the extruded aluminum bronze 41 per cent, and the cast aluminum bronze 15 per cent. The cast metal was evidently much less affected than the extruded metal.

8. The magnesium-base alloys are not as good under repeated impact as duralumin, but a comparison on a weight basis may prove more favorable to them.

9. The repeated impact test results are influenced by both the material's resistance to shock and its resistance to fatigue. Such tests should be made at different energies of blow, and if possible an impact endurance limit should be determined. Impact endurance curves for different metals often cross each other so that a comparison made at a heavy blow may be reversed at a light blow.

[For a discussion on Fatigue of Metals, see page 601.—ED.]

THE ENDURANCE RANGE OF STEEL[1]

By D. J. McAdam, Jr.[2]

Meaning of Endurance Range and Endurance Limit

Repeated cyclic variation of stress is necessary to cause fatigue failure of metal. The amount of this cyclic variation of stress determines whether or not fatigue failure within the ordinary life of a machinery part will occur. If the cyclic stress range is below a rather definite amount which varies with the physical properties of the steel, fatigue failure of a machinery part will not occur—at least within the ordinary period of usefulness. The limiting cyclic range of stress below which fatigue failure will not occur has been called the "endurance range" (**1**).[3]

In machinery parts, the position of the cyclic range of stress with reference to the elastic range varies greatly. In a rotating beam or cantilever or in a piston rod the cyclic variation may be between practically equal tensile and compressive stresses. In many machinery parts, however, the cyclic variation of bending or axial stress is between a tensile stress and an unequal compressive stress or even between two tensile stresses or two compressive stresses. In many shafts, also, the cyclic variation is between two unequal torsional stresses either in the same direction or in opposite directions.

The extent of the elastic range even in heat-treated alloy steels is not much more than twice that of the endurance range for complete reversal of stress per cycle. When one end of the endurance range is at zero stress, therefore, it is evident that even in heat-treated alloy steels the other end of the range would be not far within the elastic limit of the material unless the endurance range when it is near one end of the elastic range is much less than when it is at the middle of the elastic range. In discussion of the range, therefore, chief consideration will be given to two positions of this range within the elastic range. In one of these positions the range is between two equal and opposite stresses; in the other position the range is between zero stress and a maximum. For brevity the endurance range between equal and opposite stresses will be called the "alternation endurance range," and the endurance range between zero and a maximum stress will be called the "repetition endurance range."

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[1] Published by permission of the Secretary of the Navy.

[2] Metallurgist, U. S. Naval Engineering Experiment Station, Annapolis, Md.

[3] The boldface numbers in parentheses refer to the papers appearing in the references appended hereto.

In investigation of the endurance properties of steel, chief attention has been given to determination of the alternation endurance range. The "endurance limit" thus determined is one-half the endurance range. It would seem advisable to restrict the term "endurance limit" to this meaning and not to extend the meaning and apply the term, as some investigators have done, to the maximum stress of endurance ranges in which there is not complete reversal of stress per cycle.

PREVIOUS INVESTIGATIONS OF THE ENDURANCE RANGE OF STEEL

Recent investigations(1, 2, 3, 4, 5, 6) have given thorough information regarding the endurance limit, and hence the alternation endurance range of steel. Much less attention has been given to investigation of the endurance range when it is not at the middle of the elastic range. And yet it is of great importance to know whether or not the endurance range varies greatly in extent with variation in its position within the elastic range. The comparatively few experiments that have been made to investigate this subject have led to widely varying conclusions.

Wöhler in 1871(7) published results of an investigation of endurance properties of steel. This investigation had included repeated tension, torsion and bend tests, and rotating cantilever tests. In some of his experiments the range per cycle was between equal positive and negative stresses; on other experiments the range was between zero and a maximum stress; in still other experiments the range was between two stresses in the same direction. His conclusions were that the safety of a machinery part depends not on the maximum stress per cycle but only on the range of stress. Wöhler evidently did not mean by this, however, that the endurance range of stress does not vary somewhat with variation in the maximum stress per cycle. The values given by him for the endurance ranges of some steels vary with the maximum stress per cycle. In other words, the endurance ranges determined by Wöhler are not entirely constant for various positions with reference to the elastic range.

The tensile properties reported by Wöhler include only the tensile strength and elongation. The tensile properties of different bars from the same source differed greatly. On account of the slight attention paid to heat treatment in Wöhler's time, steel that he assumed to be uniform in properties would not now be considered sufficiently uniform for such an investigation. Since the elastic limits of his steels are not listed by Wöhler, the positions of the endurance ranges with reference to the elastic range are not known. Undoubtedly, however, in many of his experiments with cyclic range between zero and a maximum stress or between a maximum and minimum stress in the same direction, the elastic limit of the material was exceeded. Wöhler's investigation, therefore, did not determine definitely the endurance range of steels in various positions within the elastic range.

Professor Goodman(8) of the University of Leeds, basing his conclusions chiefly on results of Wöhler's tests, developed a "dynamic theory" of the relationship of the endurance range to the maximum stress per cycle. The dynamic theory assumes that a cyclic range of loading is equivalent in its effect to a suddenly applied load and that the minimum load is equivalent in its effect to a steady load. According to this theory, failure under varying load will not occur unless the nominal stress due to steady load plus twice the nominal stress due to varying load equals or exceeds the tensile strength of the metal. If Goodman's theory were true the "endurance limit" would be one-third the tensile strength, whereas many experiments have shown that the endurance limit in alloy steels is about one-half the tensile strength. If Goodman's theory were true the repetition endurance range would be one-half the tensile strength and would be three-fourths the alternation endurance range. Results of experiments to be described later are not in accordance with these requirements of Goodman's theory.

Moore and Jasper(5) investigated the endurance range of steel with widely varying ratios of maximum to minimum cyclic stress. They used a rotating specimen that could be loaded as a cantilever and subjected at the same time to uniform tensile stress by means of a spring which rotated with the specimen. The steels used in their experiments were a 3.5-per-cent nickel steel and a 0.52-per-cent carbon steel. The nickel steel was heat treated in four different ways and the carbon steel was heat treated in two different ways. The results of their experiments do not support Goodman's dynamic theory. The results indicate, however, that the endurance range varies considerably with variation of the ratio of minimum to maximum stress. According to their results the repetition endurance range for cyclic repetition is only about three-fourths the alternation endurance range. The meaning of these results will be discussed more fully below.

Results obtained by Moore and Jasper(5) and some results obtained by Haigh(9) led Jasper(10) to advance a theory which may be called the constant energy theory. According to this theory the energy applied in an endurance range cycle depends only on the metal and not on the position of the endurance range with reference to the elastic range. Jasper states that this constancy of energy per cycle of the endurance range does not extend beyond the yield point. He states that the constant energy theory applies to a tension-compression cycle, to a bending cycle, and to a torsion cycle.

It can be shown that according to the constant energy theory the algebraic difference of the squares of the limiting stresses of the endurance range would be a constant. It follows, therefore, that the repetition endurance range would be 29.3 per cent less than the alternation endurance range. This percentage difference is somewhat greater than that obtained by Moore and Jasper in their experiments.

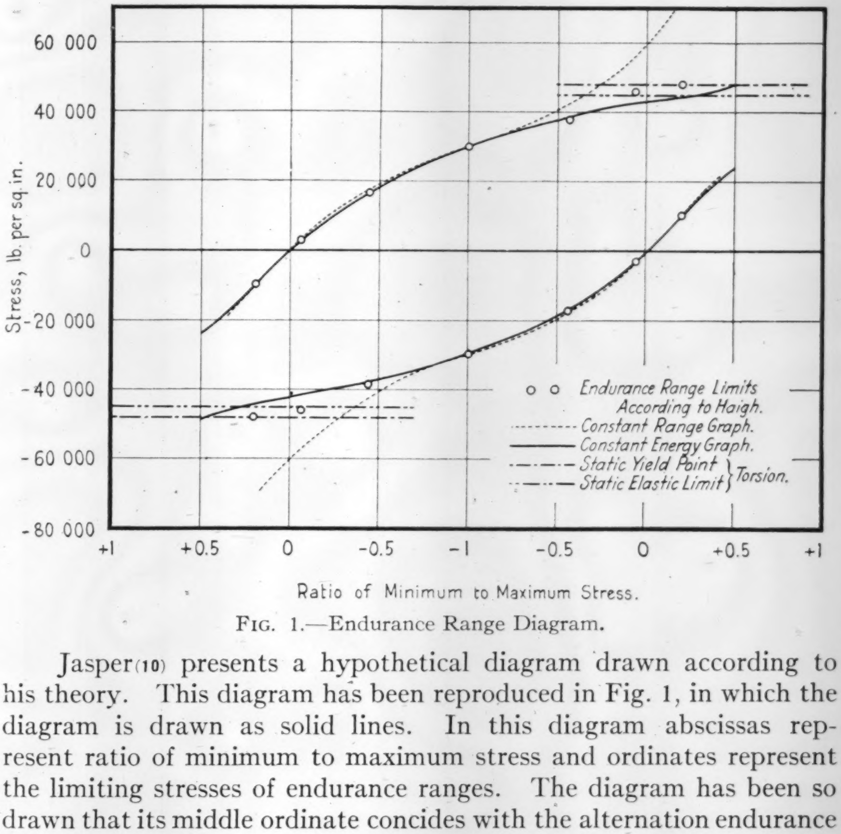

FIG. 1.—Endurance Range Diagram.

Jasper(10) presents a hypothetical diagram drawn according to his theory. This diagram has been reproduced in Fig. 1, in which the diagram is drawn as solid lines. In this diagram abscissas represent ratio of minimum to maximum stress and ordinates represent the limiting stresses of endurance ranges. The diagram has been so drawn that its middle ordinate concides with the alternation endurance range obtained by Haigh(9) with mild steel having a yield point of about 47,000 lb. per sq. in. and an "endurance limit" of 30,000 lb. per sq. in. Points representing the limiting stresses of other endurance ranges obtained by Haigh with the same steel were plotted by Jasper on the same diagram. As shown in Fig. 1 the experimental points near the middle ordinate of the diagram are on or near the constant energy graphs. The farther the points are from the middle ordinates, however, the less closely does the observed endurance range agree with the hypothetical endurance range. The points representing the highest observed stresses are well outside the constant energy diagram. The repetition endurance range obtained by Haigh was about 75 per cent of the alternation endurance range, whereas according to the constant energy theory the repetition endurance range should be about 71 per cent of the alternation endurance range.

It is worthy of note that the upper limit of the repetition endurance range obtained by Haigh is at the static yield point of the steel. It seems possible that the repetition endurance range was limited by the yield point or elastic limit and would have been greater if the yield point and elastic limit had been higher. If so, the upper limit of the repetition endurance range would have exceeded the limits of the constant energy graph even further that it does in Fig. 1.

That Jasper's diagram, shown in Fig, 1, is not conclusive evidence of the truth of the constant energy theory will be apparent, if with the same middle ordinate as a base another diagram be drawn on some plausible hypothesis other than the constant energy hypothesis. No plausible diagram drawn from the same middle ordinate could depart further from the constant energy diagram than would a diagram based on what may be called the constant range hypotheses. In Fig. 1 the diagram shown by dotted lines has been drawn on the assumption that the endurance range is constant. It will be noted that this constant range diagram does not depart far from the constant energy diagram until the elastic limit of the mild steel has been passed. If, therefore, these two diagrams representing the two most widely differing hypotheses do not separate widely until the elastic limit has been passed, it would seem that Jasper's hypothetical diagram for mild steel shown in Fig. 1 is not conclusive evidence on which to base a constant energy theory.

If instead of mild steel, an alloy steel with high elastic ratio were to be used, the hypothetical constant range and constant energy graphs would separate widely before reaching the elastic limit. With such material, therefore, it would be possible to determine definitely whether the actual endurance ranges conform to the constant energy theory or to the constant range theory or follow some intermediate relationship.

INVESTIGATION OF ENDURANCE RANGE OF STEEL AT NAVAL ENGINEERING EXPERIMENT STATION

In a previous paper(1) in a section on "The Endurance Range of Steel," reference was made to an investigation that was then in progress to determine the "length of the endurance range in various positions within and just beyond the edge of the elastic range." It was stated that "as a result of these experiments the conclusion has been reached that the variation of the endurance range within the elastic range is slight." It was also stated that within the elastic range the repetition endurance range is apparently not more than about 10 per cent less than the alternation endurance range. The opinion was expressed that "the published results of other investigations of this subject, if rightly interpreted would . . . lead to the same conclusions." As few experiments had been completed at that time no detailed results were given in support of expressed conclusions. Since the publication of the above-mentioned paper, investigation of the endurance range of steel has been continued and detailed results will now be presented.

ENDURANCE TESTING MACHINE

For investigation of the endurance range of steel, alternating-torsion machines of the spring type were used. This machine had been developed at the Naval Experiment Station. It is essentially as described in a previous paper(11), and illustrated in Fig. 1 of that paper, except that the auxiliary spring *D* has been replaced by a solid shaft.

In this machine the specimen and the two shafts between which it is held in line form one long shaft. Descending from one end of this shaft is a power arm to the lower end of which another perpendicular arm is attached by means of a bearing. The other end of the latter arm is attached to a pin eccentrically held in a rotating metal disk. This arm and pin thus serve as crank pin and connecting rod to cause oscillation of the power arm attached to the shaft that holds the specimen.

Extending from the other end of the shaft within which the specimen is held is a resisting arm—the end of which is held between two opposing calibrated springs. The torsional moment due to the action of these springs against the resisting arm opposes the oscillatory motion of the power arm and thus causes torsion in the shaft. The torsional moment is measured by measuring the magnified movement of the resisting arm against the calibrated springs. In the older form of machine the motion of the springs was magnified by means of a system of levers. In the newer machine, the motion of the springs is indicated by an optical lever system such as that used on the high-speed alternating-torsion machine of the inertia type(12).

The speed used in endurance testing with this machine is only 360 r.p.m. At higher speed the inertia effect of the shaft, resisting arm and springs would become of so much importance that accurate speed regulation would be required. Even at a speed of only 360 r.p.m. allowance must be made for the inertia effect, but accurate regulation of the speed is not necessary.

This type of machine is well adapted for making endurance tests with varying range of stress and varying ratio of minimum to maximum stress. To vary the range of stress the radius of crank-pin motion can be varied. To vary the ratio of minimum to maximum stress the connecting rod can be lengthened or shortened by means of a turnbuckle. The thread of the turnbuckle is so fine that the length of the connecting rod can be accurately adjusted. Investigation of the endurance range with this machine, therefore, involves only variation of the range of stress and of the ratio of minimum to maximum stress. Whatever the position or extent of the range, only one kind of stress is involved.

TABLE I.—CHEMICAL COMPOSITION.
All values in per cent.

Kind of Steel	Designation	C	Mn	P	S	Si	Ni	Cr	V
Carbon	AD	0.46	0.68	0.015	0.021	0.11	0.13	....	....
Carbon-Vanadium	AI	0.504	0.79	0.017	0.031	0.23	....	....	0.16
Nickel	Q	0.31	0.64	0.026	0.028	0.13	3.35	....	....
Nickel	BN	0.28	0.578	0.014	0.047	0.195	3.74	....	....
Chrome-Nickel	AO	0.368	0.681	0.012	0.013	0.13	1.36	0.65	....

TABLE II.—HEAT TREATMENT.

Kind of Steel	Designation	Heat Treatment					
		Heated to —deg. Fahr.	Time Held, hr.	Cooled in	Reheated to —deg. Fahr.	Time Held, hr.	Cooled in
Carbon	AD-2	1475	1	Water	900	2	Furnace
Carbon-Vanadium	AI-2	1460	"	"	"	"	"
Nickel	Q-17	1550	"	"	"	1	"
Nickel	BN-9	"	"	"	"	2	"
Chrome-Nickel	AO-2	"	"	"	"	"	"

For comparison, some endurance tests were made with a high-speed alternating-torsion machine of the inertia type (12). With this machine, no endurance range except the alternation endurance range can be investigated.

MATERIAL

For this investigation a carbon steel and several alloy steels were used. They were in the form of cylindrical bars about 1 in. in diameter. The chemical composition and designation of these steels are given in Table I. The Camden Forge Co. generously cooperated in this investigation by furnishing the carbon-vanadium steel.

Heat Treatment.—Material with high elastic ratio was desired so that the position of the endurance range within the elastic range could be varied as much as possible. For this reason the steels were water-quenched and drawn at the lowest practicable temperature. Details of the heat treatment are given in Table II.

Static Tension and Torsion Tests

Results of static tension and torsion tests are given in Tables III and IV. When a second numeral is added in the material designation it means that the heat treatment described in Table II was applied to a second furnace lot of material. Materials Q-17, Q-17-2, Q-17-3 and Q-17-4 are different furnace lots that have received the heat treatment listed for material Q-17 in Table II.

Table III.—Results of Tension Tests.

Each value is the average of two determinations, except as noted.

Designation	Cooled in	Drawn at —deg. Fahr.	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Johnson's Limit, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation in. 2 in., per cent	Reduction oi Area, per cent
AD-2	Water	900	131 830	81 500	....	75 000	15.8	38.3
AI-2[a]	"	"	143 500	101 000	....	93,000	17.8	48.5
Q-17	"	"	145 750	127 000	....	115 000	17.3	58.7
Q-17-2	"	"	138 750	126 500	....	121 500	18.7	64.0
Q-17-3	"	"	148 360	....	132 000	114 000	17.0	62.8
Q-17-4	"	"	146 250	133 000	130 000	121 500	17.0	59.3
BN-9	"	"	147 250	129 500	....	113 500	17.5	58.0
AO-2	"	"	160 250	....	141 000	111 000	17.5	62.3

[a] One determination only.

Table IV.—Results of Static Torsion Tests.

One test of each kind of material.

Designation	Cooled in	Drawn at —deg. Fahr.	Nominal Torsional Strength, lb. per sq. in.	Johnson's Limit, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Angle of Twist per Linear Inch at Proportional Limit, minutes	Angle of Twist per Linear Inch at Break, deg.
AD-2	Water	900	85 590	55 500	54 000	40	174
AI-2	"	"	106 870	103 000	94 190	72	129
Q-17	"	"	99 000	91 000	86 940	69	135
Q-17-2	"	"	88 760	81 500	73 650	62	247
Q-17-3	"	"	94 200	83 000	79 700	68	159
Q-17-4	"	"	93 280	87 000	84 500	70	170
BN-9	"	"	90 570	85 000	84 000	62	195
AO-2	"	"	105 150	89 300	88 000	78	190

It will be noted that high elastic ratio has been secured in this heat-treated material.

Torsional Endurance Range Determinations

Torsional endurance tests were made with alternation range of stress, with repetition range, and with several other ratios of minimum to maximum stress. With each ratio of minimum to maximum stress a series of endurance tests was made. The first test was usually made with a range of stress great enough to cause failure after very few cycles of stress. Other specimens were then tested, each at a lower range of stress than that used with the preceding specimen. With each decrease in the range of stress there was an increase in the number of cycles endured before failure. These gradual decreases in the range of stress were repeated, whenever possible, until a range was reached that would not cause failure at less than ten million cycles. This range is called the "endurance range for ten million cycles."

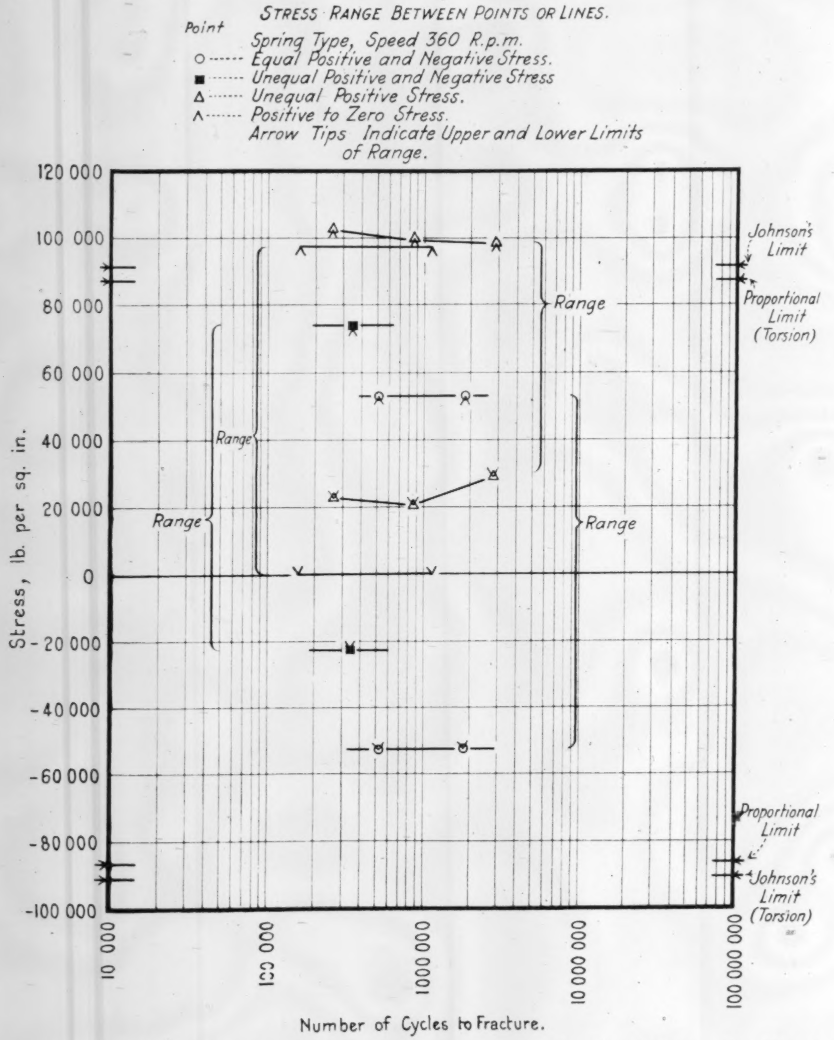

Fig. 2.—Relation of Torsion Endurance Range to Its Position Within the Elastic Range, Material Q-17, 3.35-per-cent Nickel Steel.

The endurance range of each material was thus found for two or more ratios of minimum to maximum stress.

Graphic Summary of Endurance Tests.—The results of endurance tests have been plotted on a semi-logarithmic scale and are illustrated in Figs. 2 to 9, inclusive. The two limiting stresses of each endurance test are plotted as ordinates with cycles endured as abscissas. Each endurance test, therefore, is represented graphically by two points. For each position of the endurance range there are a number of these pairs of points. Through these two series of points two idealized lines may be drawn. The vertical distances between these pairs of lines represent stress ranges and the corresponding abscissas represent cycles endured. The vertical distance between a pair of lines at an abscissa of 10,000,000 represents an endurance range.

Description of Figs. 2 to 9, inclusive.—Figs. 2 to 9, inclusive, are arranged in the chronological order in which the endurance tests were made. Figs. 2 to 5, inclusive, represent results of endurance tests on four sets of specimens of nickel steel of the same composition. Each of these sets of specimens constitutes a furnace lot that had been given the heat treatment described in Table II.

The first experiments made to determine the effect of varying the position of the endurance range are illustrated in Fig. 2. Four positions of the stress range were used in this series of tests. The four positions, as indicated by brackets in Fig. 2, were an alternation range, a repetition range, a range between unequal positive and negative stresses, and a range between two positive stresses. The two experiments made with alternation range would indicate that the alternation endurance range for 10,000,000 cycles is about 106,000 lb. per sq. in. The two experiments made with repetition range would indicate that the repetition endurance range for 10,000,000 cycles is about 95,000 lb. per sq. in. The one experiment made with partial reversal of stress would indicate that the endurance range for 10,000,000 cycles under these conditions is about 95,000 lb. per sq. in. The three experiments made in the fourth position of the range would indicate that when the minimum stress is about 30,000 lb. per sq. in. the maximum stress of the endurance range is only about 97,000 lb. per sq. in. The endurance range in this position, therefore, is only about 67,000 lb. per sq. in. The upper limit of this range is about the same as the upper limit of the repetition endurance range.

It will be noted that the upper limit of the repetition endurance range is the same as the upper limit of the shorter endurance range between two positive stresses. This would seem to indicate that the upper limit of an endurance range for this material cannot be readily increased beyond about 96,000 lb. per sq. in. Any attempt to increase this upper limit by increasing the minimum stress of the range results merely in shortening the endurance range. This maximum

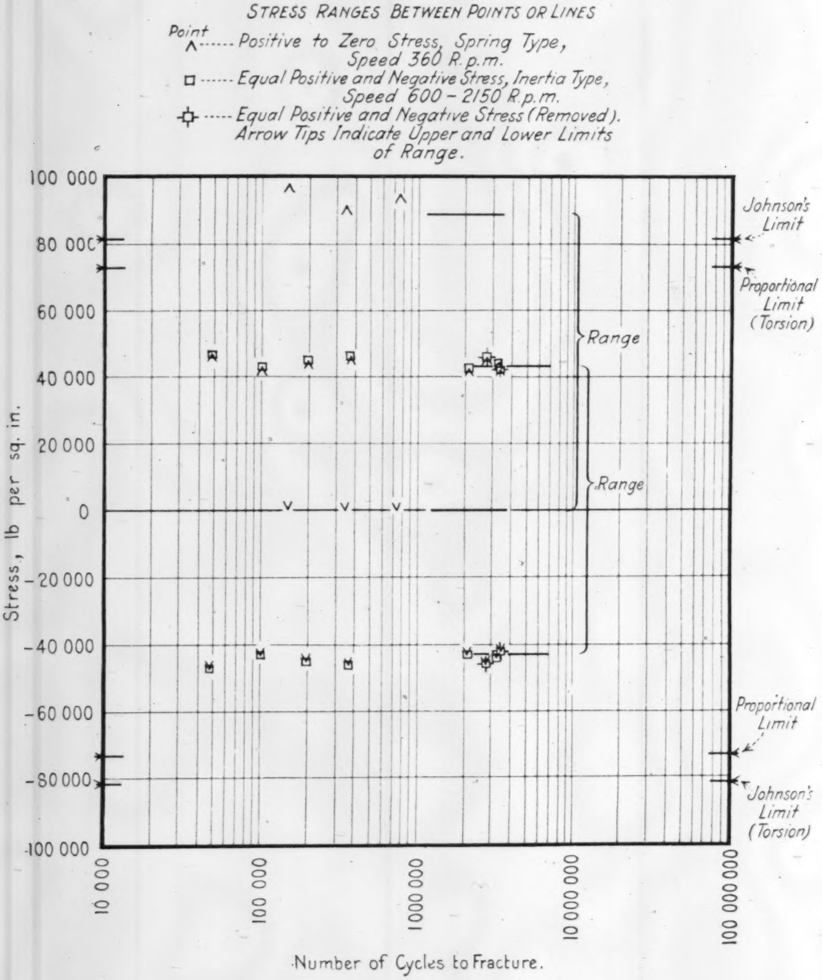

FIG. 3.—Torsion Endurance Ranges, Material Q-17-2, 3.35-per-cent Nickel Steel.

upper limit of endurance ranges is beyond the static proportional limit and slightly beyond Johnson's limit.

Since any gradual yielding of the material in a torsional endurance test with this spring type of machine would cause a redistribution of stress so as to lower the maximum stress of the range, extension of the investigation much beyond the limits of the elastic range was not desired. Since, however, there is no abrupt yield point in this material, the proportional limit and even Johnson's limit can be exceeded without causing much slow yielding of the material and consequent gradual shifting of the endurance range during an endurance test. Some experiments indicated that in none of the extra elastic stress ranges used did the shifting of the range during an endurance test amount to more than about 1000 lb. per sq. in.

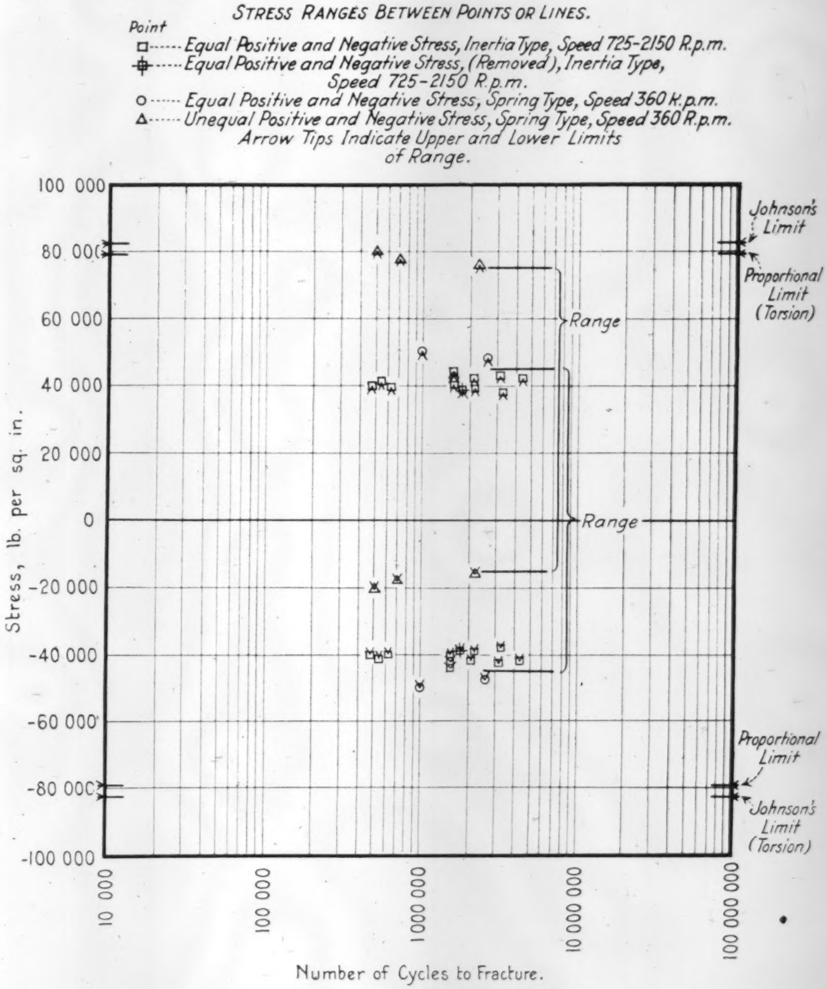

FIG. 4—Torsion Endurance Ranges, Material Q-17-3, 3.35-per-cent Nickel Steel.

The experiments illustrated in Fig. 2, therefore, apparently show that in this material the repetition endurance range, even though it extends slightly beyond the limit of the elastic range, is not more than about 10 per cent shorter than the alternation endurance range. Based on these experiments the conservative statement was made in a previous paper(1) that the endurance range apparently does not vary more than about 10 per cent with variation in its position within the elastic range.

In Fig. 3 are shown the results of a series of experiments with two positions of the endurance range. The experiments with alternation range were made with the high-speed alternating-torsion machine(12) of the inertia type. The alternation endurance range thus obtained is about 86,000 lb. per sq. in. Due to an oversight, only three specimens remained for determination of the repetition endurance range. Results with these three specimens would indicate that, in accordance with the usual stress cycle relationship, the repetition endurance range for 10,000,000 cycles would be about 88,000 lb. per sq. in. The series of experiments illustrated in Fig. 3, therefore, apparently indicates that the repetition endurance range is practically equal to the alternation endurance range. The repetition endurance range of this material extends slightly beyond the proportional limit.

A comparison between the alternation endurance range and another range is illustrated in Fig. 4. In investigation of the alternation range, two tests were made with the spring type machine and then a number of tests were made with the inertia type machine. Apparently the endurance range as obtained with the inertia machine is somewhat smaller than that obtained with the spring machine. Since numerous later experiments have shown that the two machines give equal endurance limits for the same material, the conclusion was reached that the apparent difference in the two ranges, as shown in Fig. 4, is due to differences between the individual specimens. In several series of endurance tests with nickel steels it has been found that with aging after heat treatment there is an apparent lowering of the endurance limit without corresponding decrease of tensile strength. Whether or not this apparent effect has been due to mere coincidence cannot be stated definitely at this time. In later experiments on the endurance range, however, the material after heat treatment was allowed to age for one to seven months before being tested.

For comparison with the alternation range as shown in Fig. 4 three experiments were made with a ratio of minimum to maximum stress of about -0.2. The endurance range in this position is apparently about 10,000 lb. per sq. in. This range is about the same as the average alternation endurance range as shown in Fig. 4. In this series of experiments the elastic limit was not exceeded.

Another comparison of the alternation and repetition endurance ranges is shown in Fig. 5. With both ranges the tests were made by means of the spring machine. The estimated alternation and repetition endurance ranges for 10,000,000 cycles are 82,000 and 76,000 lb. per sq. in., respectively. The repetition endurance range is well within the elastic range of this material.

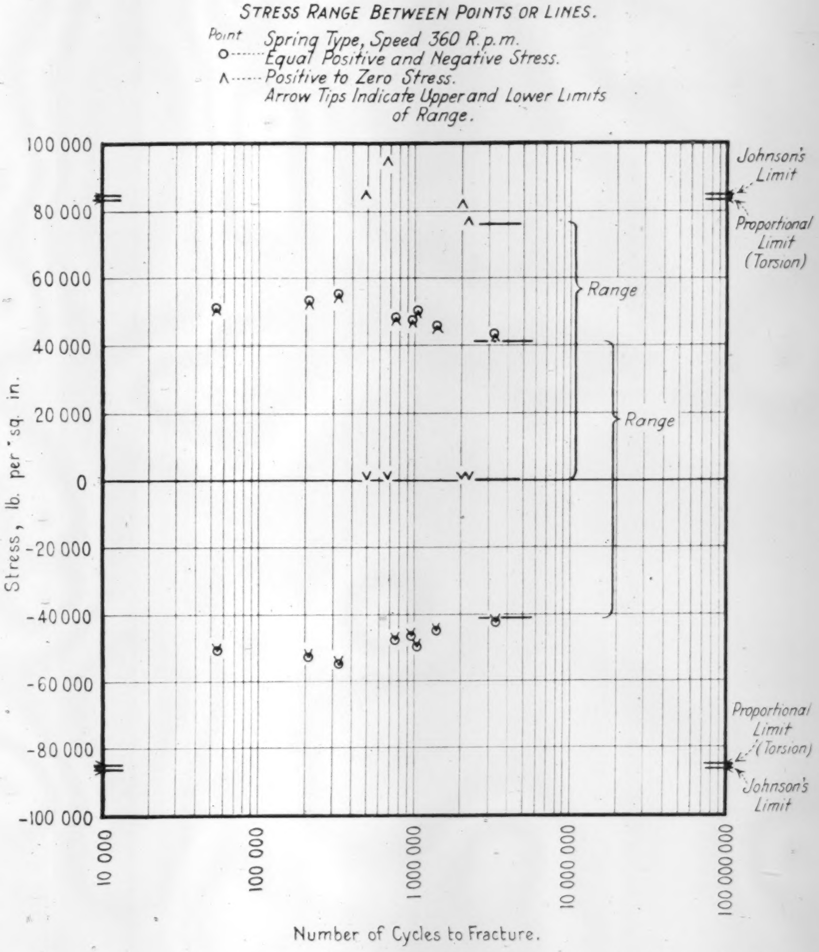

Fig. 5.—Relation of Torsion Endurance Range to Its Position Within the Elastic Range, Material Q-17-4, 3.35-per-cent Nickel Steel.

In Fig. 6 are shown results of experiments with carbon steel.

The investigation included the alternation endurance range, the repetition endurance range and an intermediate endurance range. The repetition endurance range extends slightly beyond the elastic limit. For investigation of the alternation endurance range both types of machine were used and gave concordant results. Thorough investigation of the three ranges as shown in Fig. 6 indicates that they are equal.

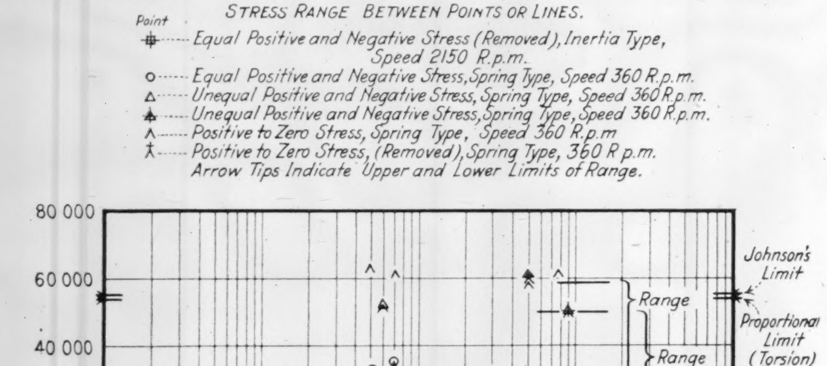

FIG. 6.—Relation of Torsion Endurance Range to Its Position Within the Elastic Range, Material AD-2, 0.46-per-cent Carbon Steel.

In Fig. 7 are shown results obtained with chrome-nickel steel. The alternation endurance range is about 94,000 lb. per sq. in. and the repetition endurance range is about 87,000 lb. per sq. in. The repetition endurance range is well within the elastic range of this material.

Fig. 8 shows results obtained with another lot of nickel steel having nearly the same composition as the nickel steel that gave the results shown in Figs. 2 to 5, inclusive. Variable results were obtained with this material. The plotted results for the upper limits of the repetition range seem to follow two distinct curves. The repetition

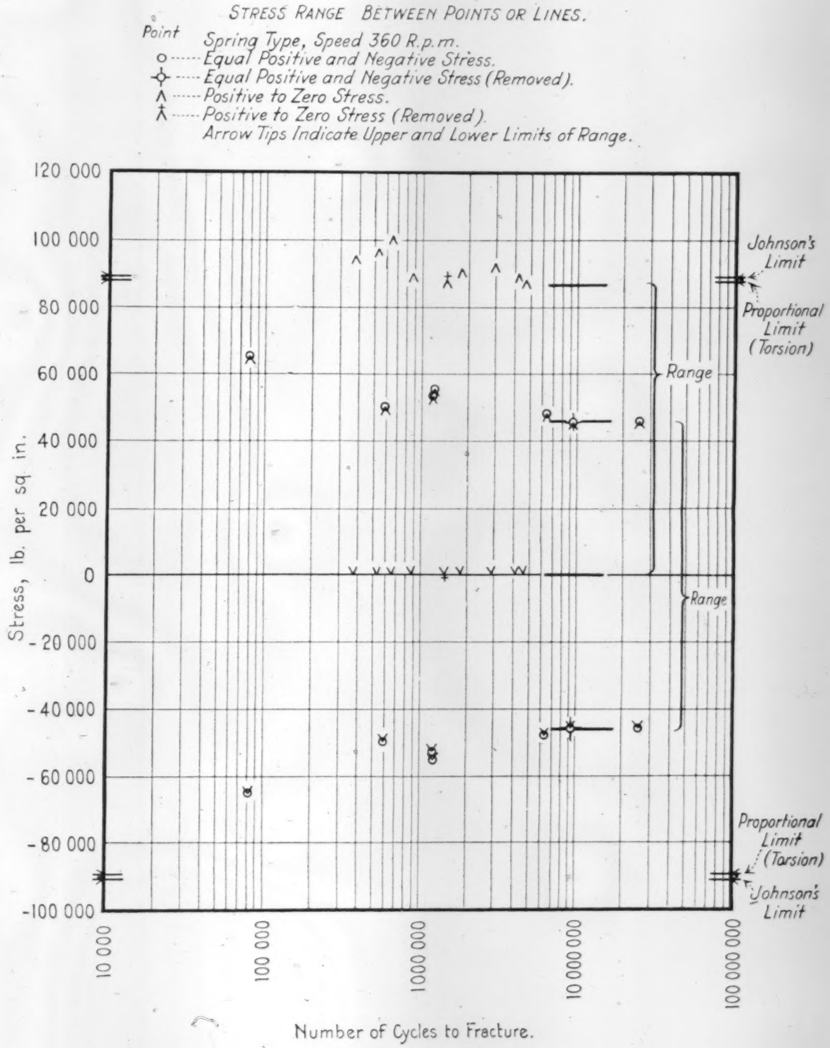

FIG. 7.—Relation of Torsion Endurance Range to Its Position Within the Elastic Range, Material AO-2, Chromium-Nickel Steel.

endurance range was assumed to be the average of the ranges indicated by these two curves. The results obtained with the alternation range were somewhat more regular, but the fact that the two specimens tested with the inertia type machine did not break indicates that the specimens of this set were less uniform in physical properties than it was hoped they would be. Nevertheless a comparison of the two ranges of stress indicates that the repetition endurance range for

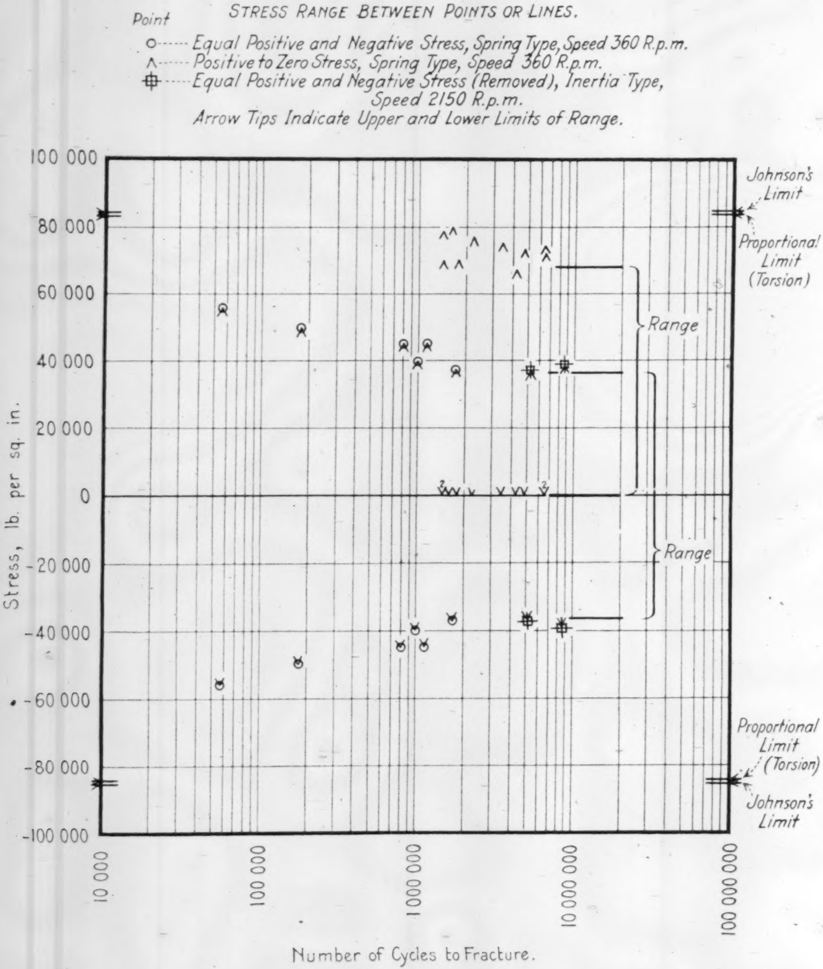

Fig. 8.—Relation of Torsion Endurance Range to Its Position Within the Elastic Range, Material BN-9, 3.35-per-cent Nickel Steel.

10,000,000 cycles is only about 5 per cent less than the alternation endurance range. All the stress ranges illustrated in Fig. 8 were within the elastic range of the material.

Fig. 9 shows results of a series of tests on carbon-vanadium steel. The alternation endurance range and the repetition endurance range

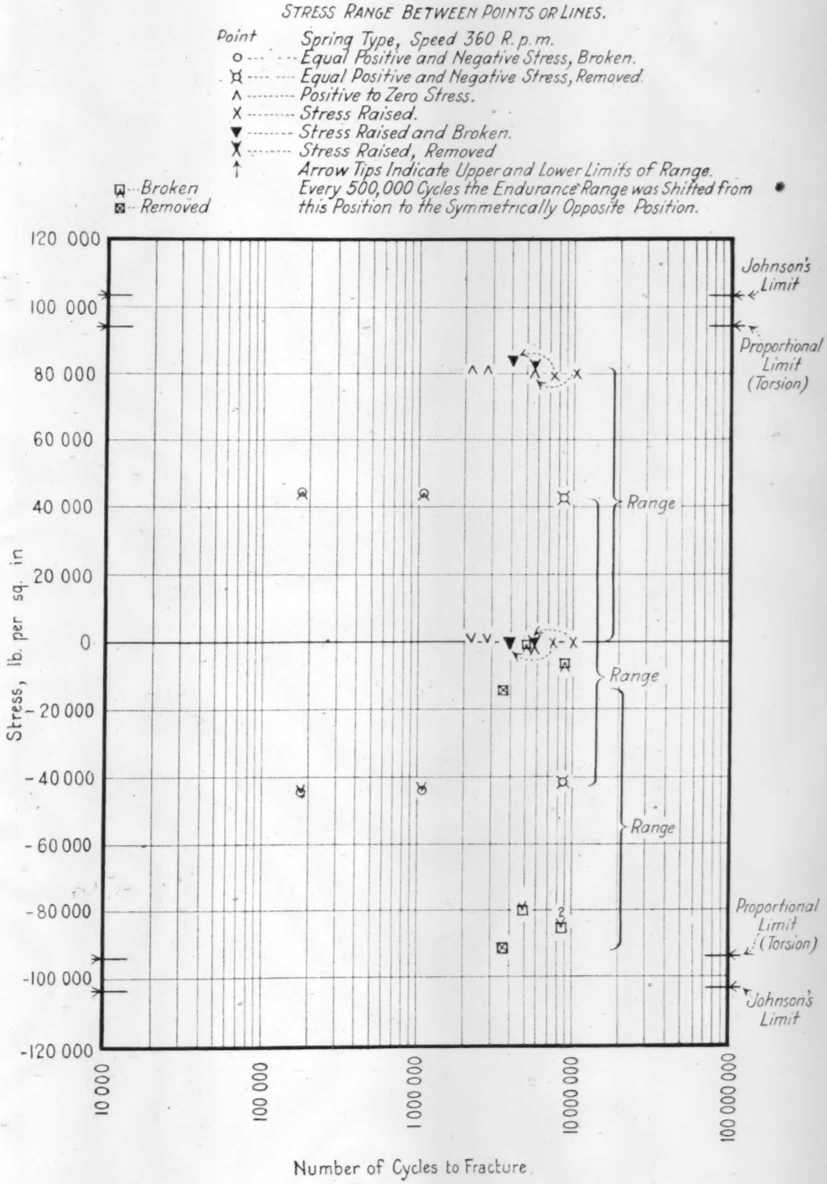

FIG. 9.—Torsion Endurance Ranges, Material AI-2, Carbon-Vanadium Steel.

and a range between two positive stresses were investigated. In investigation of the repetition endurance range two specimens, which had not failed after 7 and 10 million cycles, respectively, were subjected to increased range of stress. One of these specimens failed at the higher stress range; the other had not failed at the time the graph

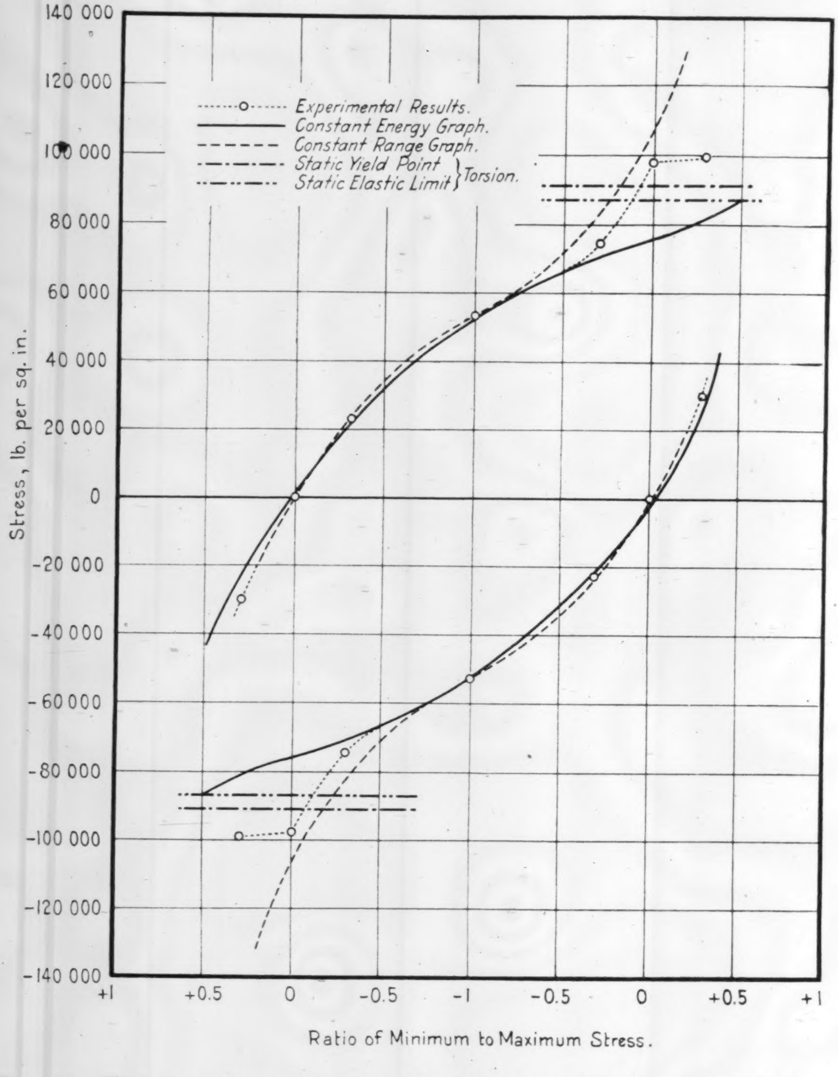

FIG. 10.—Endurance Range Diagram, Material Q-17, 3.35-per-cent Nickel Steel.

was drawn. The repetition endurance range is about 81,000 lb. per sq. in. and the alternation endurance range is apparently about 86,000 lb. per sq. in. All the stress ranges used in this series were within the elastic range. In one series of experiments, the endurance range was placed at one of the limits of the elastic range. In a few experiments the endurance range was shifted repeatedly from one end of the elastic range to the other. The endurance range when thus repeatedly shifted was not shortened.

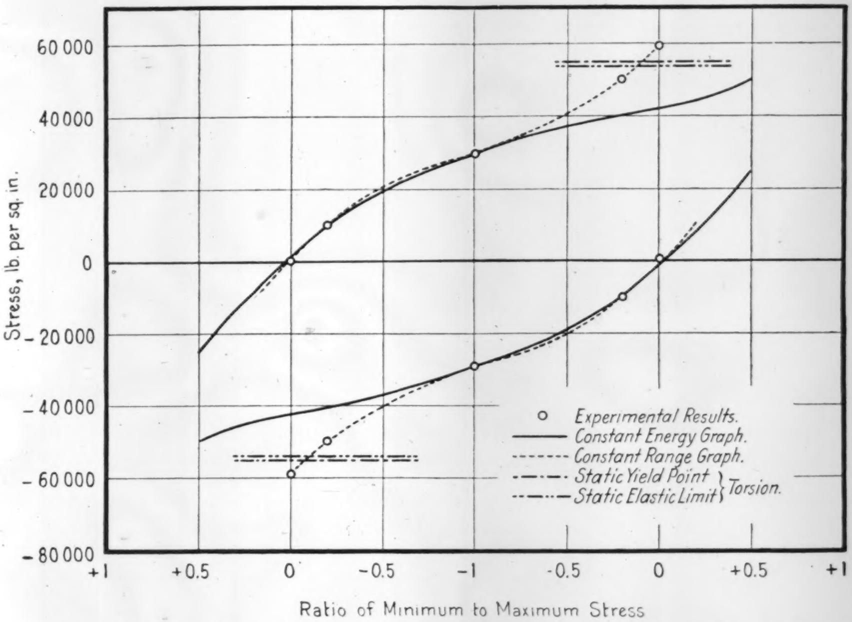

Fig. 11.—Endurance Range Diagram, Material AD-2, 0.46-per-cent Carbon Steel.

Endurance Range Diagrams

In Fig. 10, an endurance range diagram has been plotted using the results of endurance range determinations as recorded in Fig. 2. As in Jasper's endurance range diagram(10) (reproduced in Fig. 1) abscissas represent ratio of minimum to maximum stress, and ordinates represent limiting stresses of endurance ranges. Through the points representing results of experiment a graph has been drawn. Constant energy and constant range graphs also have been drawn through the ends of the experimentally determined alternation endurance range. It is evident that the graph representing results of experiment agrees more nearly with the constant range graph than with the constant energy graph. On account of the high elastic ratio of this material the experimentally determined endurance range graph has an opportunity to separate widely from the constant energy graph before the elastic limit of the material is reached.

As was pointed out in the description of Fig. 2, there is a maximum limiting stress beyond which the endurance range cannot be moved, at least until after the range has been reduced considerably in extent. The limiting stress is at about 96,000 lb. per sq. in. and is slightly beyond Johnson's limit. This limiting stress will be called the "endurance yield point."

In Fig. 11 is a diagram similar to Fig. 10 representing endurance ranges of carbon steel. In this diagram are plotted the endurance range results as recorded in Fig. 6. As shown in Fig. 11 the experimentally determined endurance diagram coincides with the constant range diagram and differs greatly from the constant energy diagram. It should be mentioned that the experimentally determined points on the left-hand side of the diagram in Figs. 10 and 11 are merely symmetrically placed duplicates of those on the right-hand side; they do not represent additional experiments.

TABLE V.

MATERIAL	PERCENTAGE VARIATION OF ENDURANCE RANGE WITHIN ELASTIC RANGE
Nickel steel, Fig. 2	10
" " " 3	0
" " " 4	0
" " " 5	7
" " " 8	5
Average for nickel steel	5
Carbon steel, Fig. 6	0
Chrome nickel steel, Fig. 7	7.5
Carbon-vanadian steel, Fig. 9	6
Average for eight sets of experiments	4.5

CONCLUSIONS FROM ENDURANCE RANGE EXPERIMENTS

In the above-described experiments five sets of nickel steel and one set each of carbon, carbon-vanadium, and chrome-nickel steel specimens were tested. The percentage difference between the alternation endurance range and the endurance range when at the edge of the elastic range may be calculated from each of these eight sets of experiments.

As shown in Table V, the average variation in endurance range of these steels within the elastic range is less than 5 per cent. The average percentage variation for nickel steel is about the same.

As indicated by some results illustrated in Figs. 2 and 10 and by some other isolated experiments not recorded in any of the graphs, there is a maximum beyond which the upper limit of the endurance range cannot readily be moved. Any attempt to move the upper limit beyond this maximum results merely in increasing the minimum stress without increase in the upper limit of the range, at least until the endurance range has been considerably shortened. This maximum upper limit has been referred to above as the "endurance yield point."

J. H. Smith(13) describes experiments made to determine similar tension-compression endurance yield points. His testing apparatus was so constructed that he could with any desired endurance range vary the mean stress while the specimen was being subjected to a stress range with cyclic frequency of about 1000 r.p.m. While varying the mean stress slowly between equal tension and compression values he measured the corresponding deflections. By gradually increasing these limits of mean stress in tension and compression he reached a point at which the rate of increase of deflection suddenly increased. The upper limits of the range at which this sudden increase in deflection occurred were compared by Smith with results of endurance tests on the same material. His conclusion was that these yield stresses determined by his deflection method are maximum upper limits of the endurance range. They, therefore, correspond to the above described "endurance yield points."

Smith's endurance yield points were not far above or below the static yield points. The steels used by him were not heat treated, but were tested as rolled. The few experiments made at the Naval Experiment Station to determine endurance yield points would indicate that the endurance yield point of steels with high elastic ratio is slightly higher than Johnson's limit.

The experiments illustrated in Figs. 2, 3 and 6 apparently show that not only within the elastic range but even up to the endurance yield point the variation of the endurance range of these steels is slight. It has even been possible in some experiments to move the upper limit of the endurance range much beyond the usual endurance yield point of the material with only slight reduction in the endurance range. Such erratic variations in the endurance range beyond the elastic range need further study. As previously stated the object of this investigation was to determine the variation of the endurance range within the elastic range.

Apparent Difference Between Results Obtained at Naval Experiment Station and Results Obtained by Moore and Jasper

The conclusions reached by Moore and Jasper(5) as a result of their investigation of the endurance range are illustrated by Fig. 41 of their *Bulletin No. 136*. In their Fig. 41, in which abscissas represent ratio of minimum to maximum stress and ordinates represent ratio of maximum stress to endurance limit, a straight line is drawn between the position (−1.0, +1.0) and the position (0, +1.5) and it is stated that this line "furnishes a fairly satisfactory graph of the results." According to these conclusions the repetition endurance range is only about three-fourths of the alternation endurance range and between these two positions the length of the range varies uniformly. It is evident that the conclusions of Moore and Jasper(5) in regard to the endurance range of steel are very different from the above-stated conclusions reached at the Naval Experiment Station.

The experiments of Moore and Jasper(5) were made with rotating cantilever specimens. Their results, therefore, represent tension-compression endurance ranges, whereas the results herewith presented represent torsion endurance ranges. It is possible that the tension-compression endurance range relation is different from the torsion endurance range relation. It may be that in tension-compression cycles, the endurance range energy is constant, whereas in torsion cycles the endurance range is approximately constant. While this explanation may be correct, it does not appear sufficiently plausible to justify its acceptance until other possible explanations have been considered.

It seems probable that the results of these two investigations, if rightly interpreted, would lead to the same conclusions in regard to the endurance range of steel. Moore and Jasper(5) state that their endurance limits (under reversed stress) were "considerably lower, in one case as much as 10 per cent, than the corresponding limits obtained by the Farmer rotating beam machine." It seems probable that the error in their stress measurements was somewhat greater when the endurance range was at or beyond the limits of the elastic range. Assuming, however, that their stress measurements are 10 per cent too low, the relationship of their range stresses to static proportional limits would be considerably altered. This alteration would make possible a reinterpretation of their results.

As an illustration, some of the results assembled by Moore and Jasper in Table 13 of their Bulletin(5) have been selected and are given in Table VI.

A study of the endurance ranges of the first of the three steels listed in Table VI makes it evident that the maximum stress of the endurance range cannot easily be increased beyond about 81,000 lb. per sq. in. At this value, the maximum stress remains while the minimum stress increases from −32,400 to +23,100. With further increase of the minimum stress to +44,000, the maximum stress increases to only 88,000. Evidently a stress listed at about 81,000 lb. per sq. in. is an "endurance yield point" of this material. This "endurance yield point" as recorded is about equal to the static proportional limit. It is probable, however, that the endurance yield point is actually about 10 per cent higher than the value listed in the table and is approximately equal to the static yield point. With variation in the position of the endurance range, the range length apparently varies only about 5 per cent unless the endurance yield point is reached.

Table VI.—Endurance Ranges for Various Combinations of Tensile and Reversed Bending Stresses.

(Selected from a paper by Moore and Jasper)(**5**).

Steel No.	Steel Designation	Maximum Stress, lb. per sq. in.	Minimum Stress, lb. per sq. in.	Endurance Range, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Yield Point, lb. per sq. in.
7	3.5 per cent nickel, treatment B.	60 000	−60 000	120 000	82 400	91 100
		68 000	−45 000	113 000	....	....
		81 000	−32 000	113 400	....	....
		83 000	0	83 000	....	....
		81 000	23 100	57 000	....	....
		88 000	44 000	44 000	....	....
7	3.5 per cent nickel, treatment C.	61 000	−61 000	122 000	93 000	94 200
		66 000	−52 800	118 000	....	....
		72 000	−43 200	115 200	....	....
		86 000	−34 000	120 400	....	....
		96 000	−19 200	115 200	....	....
		99 000	0	99 000	....	....
		101 000	50 500	50 500	....	....
10a	0.53 per cent carbon, sorbitic...	48 000	−48 000	96 000	67 700	69 700
		55 000	−36 700	91 700	....	....
		62 000	−24 800	86 800	....	....
		65 000	0	65 000	....	....
		66 000	18 900	47 000	....	....

Examination of the endurance ranges of the second steel listed in Table VI leads to similar conclusions. Between the stresses listed in the table as 86,000 to 96,000 lb. per sq. in. is the endurance yield point of this material. Until this point is reached the endurance range varies only about 4 per cent. In an attempt to raise the maximum stress beyond the endurance yield point the minimum stress was increased about 70,000 lb. per sq. in. while the maximum stress increased only 5000 lb. per sq. in. The endurance yield point as listed is about equal to the static proportional limit. Actually it is probably somewhat higher than the static yield point.

Examination of the endurance ranges of the third steel listed in Table VI leads to similar conclusions. A stress slightly below the maximum stress listed in the table as 62,000 lb. per sq. in. is probably the endurance yield point of this material. To increase the maximum stress of the endurance range from 62,000 to 66,000 requires an increase of 43,700 lb. per sq. in. in the minimum stress. The actual stress at the endurance yield point is probably not far from the static yield point, 69,700 lb. per sq. in. If the maximum stress of the endurance range is kept below the endurance yield point, the variation of the range length with variation in position is probably less than 10 per cent.

According to this interpretation of the results obtained by Moore and Jasper the variation of the endurance range of these three steels is slight, provided the endurance yield point is not exceeded. Within the elastic range, the actual variation of the tension-compression endurance range is probably no greater than the variation in the torsion endurance range. It seems probable that a right interpretation of Moore and Jasper's results would lead to the same conclusions in regard to the tension-compression endurance range that have been expressed above in regard to the torsion endurance range.

If constant range and constant energy graphs were drawn in Fig. 41 of Moore and Jasper's paper, neither of these graphs would depart widely from their straight line graph until the 0.5 abscissa is reached. To determine the endurance range relationship conclusively, the repetition endurance range, or a range as near as possible to the repetition endurance range without exceeding the elastic range, should be investigated. With a tension-compression or with a bending cycle it is difficult or impossible to obtain a repetition endurance range without exceeding the elastic range. Since the ratio of proportional limit to endurance limit is higher in torsion than in tension it is easy, without exceeding the elastic range, to investigate the repetition endurance range in torsion.

PRACTICAL APPLICATION OF RESULTS OF ENDURANCE RANGE INVESTIGATION

The information obtained by investigation of the endurance range of steel will have practical application in the design of machinery parts that are subject to torsion fatigue. It will be of especial value in the design of heat-treated alloy-steel shafting. In such shafting the high elastic ratio makes possible a wide variation in the position of the endurance range within the elastic range. The endurance range investigation has shown that the variation in the extent of the endurance range within the elastic range is not more than about 5 per cent. When, therefore, the endurance limit (for complete reversal of stress per cycle) has been determined, the calculation of other so-called endurance limits is unnecessary. The endurance range when in the middle of elastic range is twice the endurance limit, and the endurance range when at one end of the elastic range is not more than about 5 per cent less.

It is possible that the calculation of endurance ranges for machinery parts, subject to tension-compression or bending ranges of stress is not so simple as the calculation of endurance ranges for machinery parts subject to a range of torsional or shearing stress. It seems not impossible, however, that a reinterpretation of the results of the investigation of Moore and Jasper(5) may show that within the elastic range the endurance ranges of any kind of stress follow more nearly a constant range relationship than a constant energy relationship.

The results of this investigation emphasize the superiority of steel of high elastic ratio, as well as high tensile strength, for fatigue-resistant machinery parts. Increase in the elastic ratio increases the ratio of endurance limit to tensile and torsional strength (endurance static ratio)(1,14). With steel of high elastic ratio, therefore, the endurance range is greater in proportion to tensile and torsional strength than with steel of low elastic ratio. With steel of high elastic ratio it is possible also to utilize the full endurance range with wide variation in the ratio of minimum to maximum stress. With steel of low elastic ratio the full endurance range can be utilized only when the range is between nearly equal and opposite stresses.

Acknowledgment.—The author wishes to acknowledge the encouragement in this work received from Captain P. B. Dungan, U. S. Navy, Officer in Charge, U. S. Naval Engineering Experiment Station; and to acknowledge the assistance received from Mr. George F. Wohlgemuth, Associate Metallurgist; and Messrs. E. A. Snader and A. P. Vandermast, Laboratorians at the Naval Experiment Station.

REFERENCES

(1) D. J. McAdam, Jr., "Endurance Properties of Steel: Their Relation to Other Physical Properties and to Chemical Composition," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 56 (1923).

(2) D. J. McAdam, Jr., "Endurance of Steel under Repeated Stresses," *Chemical and Metallurgical Engineering*, December 14, 1921.

(3) H. F. Moore and J. B. Kommers, "An Investigation of the Fatigue of Metals," *Bulletin No. 124*, University of Illinois, Vol. 19, No. 8, October 24, 1921.

(4) H. F. Moore, J. B. Kommers and T. M. Jasper, "Fatigue or Progressive Failure of Metals under Repeated Stress," *Proceedings*, Am. Soc. Testing Mats., Vol. 22, Part II, p. 266 (1922).

(5) H. F. Moore and T. M. Jasper, "An Investigation of the Fatigue of Metals, *Bulletin No. 136*, University of Illinois, Vol. 20, No. 37, May 14, 1923.

(6) D. J. McAdam, Jr., "Endurance Properties of Corrosion-Resistant Steels," *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part II, p. 273 (1924).[1]

(7) Investigations by Wöhler and others are discussed by W. C. Unwin, "The Testing of Materials of Construction," Chapter XVI, 1910.

(8) Goodman, "Mechanics Applied to Engineering," Ninth Ed., p. 634.

(9) Bernard P. Haigh, "The Endurance of Metals under Alternating Stresses," paper read before West of Scotland Iron and Steel Inst., November, 1915.

(10) T. M. Jasper, "The Value of the Energy Relation in the Testing of Ferrous Metals at Varying Ranges of Stress and at Intermediate and High Temperatures," *Philosophical Magazine*, Vol. XLVI, October, 1923.

(11) D. J. McAdam, Jr., "An Alternating Torsion Testing Machine," *Proceedings*, Am. Soc. Testing Mats., Vol. XVII, Part II, p. 599 (1917).

(12) D. J. McAdam, Jr., "A High-Speed Alternating Torsion Testing Machine," *Proceedings*, Am. Soc. Testing Mats., Vol. XX, Part II, p. 366 (1920).

(13) J. H. Smith, "Some Experiments on Fatigue of Metals," *Journal*, Iron and Steel Inst., No. II, p. 246 (1910).

(14) D. J. McAdam, Jr., "Accelerated Fatigue Tests and Some Endurance Properties of Metals," *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part II, p. 454 (1924).[1]

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[1] The present Volume.—ED.

DISCUSSION ON FATIGUE OF METALS

Mr. Moore.

MR. H. F. MOORE.[1]—The Society is to be congratulated on the four very fruitful papers on the subject of fatigue of metals. In three of the papers there is discussed the question of how to reduce the time required to make a reliable fatigue test of a metal. In the papers by Messrs. Gillett and Mack and by Mr. Moore there is given a considerable amount of test data on the time necessary to carry out unaccelerated fatigue tests so as to be sure the endurance limit is actually shown. So far as the speaker knows this important point has not been carefully studied before, and testing engineers should carefully examine the logarithmic diagram given by Mr. Moore and the comparison of times required for hard and for mild steel given by Mr. Gillett before making a determination of endurance limit for unfamiliar metal.

The "coaxing" test described by Mr. Gillett seems promising, if used with care, and may possibly be developed into a useful commercial test. The limitations of the rise-of-temperature test and of the running deflection test are being marked out and their field of usefulness outlined. To the workers in fatigue of metals at the University of Illinois, it seems that both the rise-of-temperature test and the running deflection test indicate the beginning of intra-crystallin slip rather than of fatigue failure. For wrought ferrous metals (except very hard steel) and possibly for some other metals it happens that such slip takes place at about the same stress as does the beginning of a spreading fatigue fracture, but this does not seem to be true for all metals. Accelerated tests should not be used to determine the endurance limit of a metal until for metals similar in general chemical composition and in crystallin structure there have been run long-time fatigue tests to check the results of accelerated tests.

Mr. McAdam's accelerated fatigue test seems especially worthy of further study. He has used it in connection with alternating-torsion tests, but there seems no reason why an analagous test could not be developed for alternating flexure, or for alternating axial stress (tension-compression). The strong point of his accelerated test, as the speaker sees it, is that the fatigue failure starts normally, or at least under conditions nearly approaching normal, and that it is the *progress* of the fatigue failure which is accelerated.

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[1] Professor of Engineering Materials, University of Illinois.

Mr. Moore. The question of range of stress raised in Mr. McAdam's second paper is of interest. His results are all on repeated torsion tests, producing repeated shearing stress. Recent tests at the University of Illinois[1] check his conclusion that for repeated shearing stress the *range* of fatigue stress varies but little whether the cycles of stress involve complete reversal or a variation of stress from zero to a maximum. So far, however, for repeated flexural stresses, tests have shown that for cycles of stress varying from zero to a maximum the range is about 75 per cent of the range for complete alternation, with the limiting condition that under no conditions is it safe to exceed the yield point of the metal. The question of range of stress for various different cycles of repeated stress demands further study; at present it seems to the speaker that the assumption of a diminished range for stress repeated but not reversed is on the side of safety in design.

The speaker wishes to cite a few test results obtained in the laboratories of the University of Illinois, which check points raised in these papers. Mr. McAdam gives an endurance limit for copper in reversed torsion at 6000 to 7000 lb. per sq. in. At Illinois, annealed copper in reversed flexure developed an endurance limit of about 10,000 lb. per sq. in. Results on Muntz metal also seem to be checked by values obtained at Illinois. The low values given by R. R. Moore for the ratio of endurance limit to tensile strength of non-ferrous metals are checked by results at Illinois, as are the high values for ratio of endurance limit to elastic limit (proportional limit). The short-specimen rotating-beam machine described by R. R. Moore is quite similar to several in use at Illinois, and seems to be a very good form of machine. I think this form was first used by Mr. Ono of Tokyo.

The speaker in conclusion wishes to call attention to two very useful terms in Mr. Gillett's paper, "scatter" applied to the grouping of points determined from test data round the line chosen to represent the general action, and "stress-raiser" applied to cracks, flaws, notches or grooves in a member subjected to repeated stress. The speaker hopes that these two terms will come into general use.

Mr. Lessells. MR. J. M. LESSELLS.[2]—The paper by Gillett and Mack seems to contain some new data and will no doubt be appreciated by engineers in general. There are one or two points, however, which I should like to discuss in detail.

On the question of internal stress, the ratio adopted by me of yield point to proportional limit was chosen because it seemed to

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[1] University of Illinois Engineering Experiment Station *Bulletin No. 142.*

[2] Mechanical Engineer, Research Department, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

Mr. Lessells.

express the fundamental conception of shape of stress-strain diagram for those early stages of deformation. It was put forward as provisional only, since other ratios may express this idea just as well. The reason for putting forward the question of internal stress was to emphasize again the importance which the elastic properties bear on the breakdown by fatigue.

The endurance limit being analogous to the ultimate stress in tension in the respect that both represent limiting stresses, it is natural to expect some relation between them. This thought, of course, is not new, having been pointed out by Gerber.[1] We can not, however, afford to forget the work which was later developed by Bauschinger[2] on the natural elastic limit theory, a work which was later confirmed by Bairstow.[3] These later works emphasized the importance of the elastic properties and it may be well to bear these facts in mind. The work on internal stress previously mentioned emphasizes this fact from a different angle. The remarks made on the impossibility of applying such a theory to steel with non-metallic inclusions or with directional properties appear to be irrelevant because it is presupposed that we are dealing with steels possessing similarity in microstructure.

There seems to be evidence to conclude that the tension test diagram shows internal stress by a change in the ratio of yield point to proportional limit and that this considerably lowers the ratio which the endurance limit bears to the ultimate stress.

The authors state that ductility appears to have no effect on the endurance limit. While this appears to be true, it might be accepted in some quarters that in this respect the ductility properties have very little value to the designer. This of course is very far from being the case. In those types of construction where changes in section and holes or grooves are necessary, stress concentration takes place. In certain cases the maximum stress due to such concentration may be two or three times the average stress over the section.[4] With structural steels, however, possessing as they do the properties of ductility, the reduction in endurance limit for these stress concentrations is very much less[5] than the stress concentration would indicate and this fact is due entirely to the ductility properties, allowing the material to adjust itself to the new conditions imposed on it so that a more favorable redistribution of stress is possible. While we

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[1] Gerber, *Zeitschrift für Baukunde*, München, 1874.

[2] Bauschinger, *Dingler's Polytechnische Journal*, Band 266, 1886.

[3] Bairstow, *Philosophical Transactions*, Royal Soc., 1911.

[4] S. Timoshenko, *Journal*, Franklin Inst., April, 1924.

[5] Stanton and Bairstow, *Proceedings*, Inst. Civil Engrs., 1906.

Mr. Lessells. would expect a brittle material such as glass to be affected in the same degree as the stress concentration indicates, it is otherwise with materials possessing ductility properties.

With reference to the remarks regarding the relationship between the impact test, either repeated or single blow, and endurance limit, it is difficult to see any reason why the single blow impact values should be so related since they are entirely different tests. There appears, however, a relation which is to be expected between Stanton values and endurance values provided the number of blows is carried sufficiently far. Stanton's[1] paper on the subject shows that very clearly. The author has since confirmed this for many steels and suggests the thought that we have here, while not a short time-test, nevertheless a test requiring shorter time than the ordinary fatigue tests.

Referring to Fig. 1, if we have the repeated impact curves for two steels possessing more or less similarity in microstructure and the endurance limit for steel A be p_A lb. per sq. in., then from the curves, the heights x and y can be obtained and the endurance limit for steel B will become

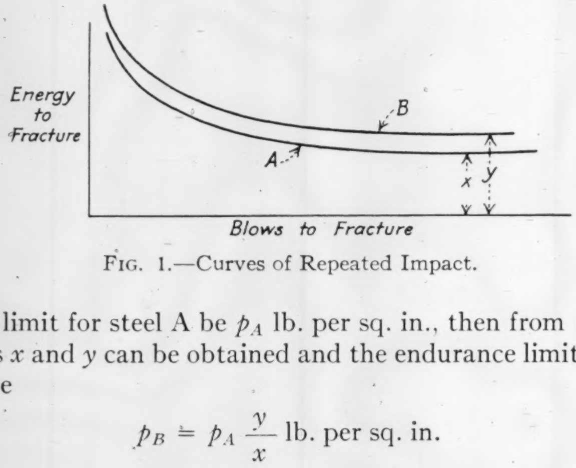

FIG. 1.—Curves of Repeated Impact.

$$p_B \doteq p_A \frac{y}{x} \text{ lb. per sq. in.}$$

With reference to the effects of vanadium, I agree that with cast material there is only a slight increase of the ratio of endurance limit to ultimate stress. This has now been confirmed for forged material in the normalized condition and higher ratios are obtained than can ever be expected for normalized carbon steels, due to the finer grain obtained with these vanadium steels.

Referring now to Mr. McAdam's paper on accelerated fatigue tests, the following remarks may be of interest.

In the first place, the author refers to "deflection method" while the test bar is under cyclical torsional shear stress. I wonder whether some other name could not be proposed, using deflection method purely for the bending type of test. It is interesting to note that he finds the endurance limit as found by the short-time test is not in good agreement with that found by the long-time test. This confirms my own contribution of last year to this Society,[1] where it was shown that the endurance limit as found by the deflection method was not in good agreement with that found for long-time tests. This applied to certain steels and non-ferrous alloys. In the second place, I presume the accelerated fatigue method is a further application of the method used by Gough in which time effect is considered. This, of course, as pointed out by me, may be the reason why the deflection method fails. **Mr. Lessells.**

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[1] Stanton, *Proceedings*, Inst. Mechanical Engrs., November, 1908.

It is very interesting to note that we are returning to a consideration of the elastic properties in addition to the strength properties in analyzing the mechanism of fatigue. This seems to be a correct attitude since it is in general accepted that whatever may be the cause of final rupture, the beginning of that state, namely, the production of slip bands, must depend in large degree upon the elastic constants of the metal. The fact that these slip bands appear at stresses below the proportional limit is irrelevant, this being due to unfavorably situated crystals. It seems to me that the theory of Bauschinger's natural elastic limits, later confirmed by the work of Bairstow, still holds the field, at least subject to possibly some slight modification.

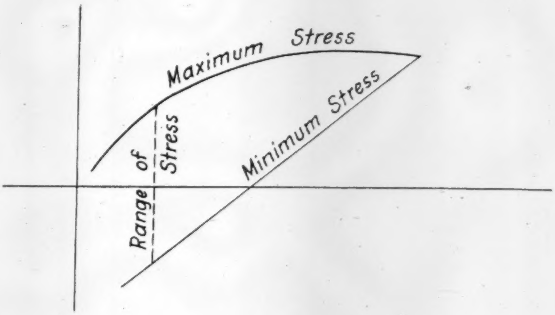

FIG. 2.

Under Conclusions in McAdam's paper on "The Endurance Range of Steel," the auther states "there is a maximum beyond which the upper limit of the endurance range cannot readily be moved. Any attempt to move the upper limit beyond the maximum results merely in increasing the minimum stress without increase in the upper limit

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[1] Discussion on Endurance Testing of Metals, *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 122 (1923).

Mr. Lessells. of the range, at least until the endurance range has been considerably shortened." I ask is this a new thought because the parabolic relation of Gerber seems to indicate this and certain experimental data are available on the subject. (See Fig. 2.)

Referring to R. R. Moore's paper on "Resistance of Metals to Repeated Static and Impact Stresses," I see that the author calls a fatigue test a static test. This is difficult to accept. The term "fatigue test" is a good one, why not adhere to it? The author draws attention to the fact that the endurance properties of metals are not affected in the same proportion as the concentration of stress would show. I ask him would he expect this to be the case because much literature has been published on the subject. It is here that we get a true use for ductility, because the material is so able by these properties to adjust itself to the condition imposed on it by concentration of stress produced by the notch that a redistribution of stress is possible. While we would expect a material such as glass to be affected in the same degree as the stress concentration shows, it is otherwise with ductile materials. The remarks on repeated shock tests give nothing new because the speaker has indicated these facts elsewhere. The statement that this curve of repeated impact gives shock and fatigue conditions belongs, of course, to Stanton's fundamental contribution to the subject.

I am rather surprised that on such a subject the author makes no mention of Stodola's published work on fillets where the effect of ductility is shown, or H. F. Moore's work, or Stanton's work on screw threads and on repeated impact.

Mr. Tuckerman. MR. L. B. TUCKERMAN[1].—A point which was implied in Mr. H. F. Moore's discussion needs further emphasis. We all feel the need of short-time tests for the fatigue properties of metals, tests which we can put into the ordinary laboratory as routine test procedure, and so every attempt to obtain such methods which will give us a true idea of the fatigue characteristics of a metal is of value. In this respect the "coaxing" method of Mr. Gillett and the automatic increase of stress by Mr. McAdam are valuable, but I want to give again the caution which has been the burden of my discussion of several papers. All of these short-time or accelerated methods need and must have, before we can rely upon them, the confirmation of the old-fashioned endurance run to failure, carried to as many alternations of stress as is necessary to meet the practical conditions. If possible, they should be carried to an endurance limit, and as you all know, that means very long continued tests for the non-ferrous metals.

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[1] Engineer Physicist, U. S. Bureau of Standards, Washington, D. C.

Mr. Tuckerman.

Mr. Moore has raised our hopes again in regard to the possibility of getting some idea of an endurance limit of non-ferrous metals without waiting for our grandchildren to grow up. He is obtaining, I believe, in the neighborhood of 50,000,000 to 200,000,000 alternations of stress, evidences of an endurance limit. If at 200,000,000 alternations of stress there are definite indications of the fatigue limit in the case of some of the non-ferrous alloys such as are found in ferrous metals below 10,000,000, the results are of great value.

I want to discuss a little in detail the phenomenon which is the basis of Mr. McAdam's accelerated test. He uses the alternating-torsion inertia machine, so arranged that any increase of deflection, that is, increase of angle of twist of the specimen under a constant angle of twist and constant speed of his crank, automatically increases the inertial forces, and that, of course, produces the automatic increase of stress. The phenomenon that he is observing is a secondary phenomenon, arising from the Smith-Gough load-deflection curve. He has pointed that out, but in that connection some tests which we have carried out incidentally at the Bureau of Standards are of interest. Mr. Aitchison, who has been doing some of that work in our laboratory, investigated the time effect, rather inconclusively, because it was incidental to some other work in the Sondericker type of machine, in which the load is necessarily constant. He found that the break of the load-deflection curve was giving him different results, not very largely different, but still different, due to the accidental differences of the time in which he applied his increments of load. He started to investigate that effect and found that as you increased the time, the load at which the break in the load-deflection curve would occur in the method which has been devised by Smith and worked on by Gough, gave a definite curve. That is, almost immediately after the aplication of a certain load the curve would break. If you waited a minute it would break at a slightly lower load, and if you waited for ten minutes at a still lower load. There seemed, however, to be some sort of a limit to that particular phenomenon, although enough experiments have not been made to determine it definitely.

The phenomenon which Mr. McAdam observed and used for his accelerated test is a combination of the two things, this increase of deflection as a time effect, combined with the automatic increase of stress due to that increase of deflection.

There have been one or two comments which were made in the papers and on the papers which seemed to me to leave a somewhat false impression. We all know that the endurance limit of steel is not the endurance limit of steel, but the endurance limit of a certain

Mr. Tuckerman. kind of steel, and so, in speaking of the endurance limit of duralumin I think we should recognize that if duralumin has an endurance limit there are different endurance limits for different kinds of duralumin. The work that we have been doing at the Bureau of Standards on sheet metal, in materials supposedly identical in structure, bought under the same specifications and not showing recognizable differences in microstructure, shows definite differences in fatigue characteristics at 100,000,000 alternations of stress, from about 12,000 lb. per sq. in. to about 16,000 or 17,000 lb. per sq. in. Those differences do not show up markedly at ten million alternations of stress, but are very appreciable and noticeable at one hundred million alternations of stress, so that I feel we must recognize that in these non-ferrous metals, as in steel, we are not dealing with a material uniform in its fatigue characteristics, but in materials which may vary. It would be very nice if we could have a fatigue limit for copper, steel or brass, because then we could simply forget about fatigue tests after having once made them, but the differences are there, and mean that for an estimation of the value of those materials we must rely upon tests of the particular material we are using.

One other comment, upon the ratios of endurance limit to specific gravity which were given in Mr. R. R. Moore's paper. Comparisons of that kind are of very great value. The ratios between tensile strength, yield point, endurance limit and other properties and the density of the material are ratios which we ought to remember in considering the possibilities of the use of these various materials. There is one point in connection with them, however, which I have found is not always recognized. The lighter alloys in members subjected to tensile stresses are practically valuable in the ratio of tensile strength to density or yield point to density or endurance limit to density; but when you use them in compression members, they become relatively much more advantageous. In compression members the cross-section comes in. That is, you can make with the lighter alloys for the same mass much larger cross-sectional areas, and consequently, for the same amount of material you can produce lower stresses. I have attempted once or twice to express that in a general form, but found that it depends so much upon the shape of the specimen that it cannot be expressed as a general statement. In some shapes of compression members the value of the lighter material is approximately in proportion to the strength property divided by the square of the density of the material, and for all practical cases it lies in between the two limits, strength property divided by density and strength property divided by the square of the density of the material.

MR. H. A. ANDERSON.[1]—I think the average engineer is hopeful that the exhaustive fatigue investigators will go a step further than Mr. Tuckerman has stated, namely, giving us a quick fatigue test, and will go to the point where they may determine a relationship between the static tensile properties and the fatigue endurance limit.

Mr. Anderson.

Looking over, very superficially, these papers that have been presented this morning, it appears that there is a relationship between the endurance limit for repeated bending and the tensile strength—for steels—of one to two or fifty per cent, and for non-ferrous materials of one to three or about thirty-three per cent.

Mr. R. R. Moore stated definitely that he did not believe that there is any relationship between the proportional limit in tension and the fatigue endurance limit. In contrast with this view I want to call attention to the table which Mr. McAdam abstracted from H. F. Moore's results showing the fatigue endurance limit where the stresses were not of opposite kinds. They were not reversals of stress, but simply repetitions of tensile stresses. In that case the agreement between the proportional limit and the endurance limit was very close.

I think that the next point of attack where we have to hope for success in correlating static tensile results and fatigue endurance results, is in changing our type of static tension tests so that we determine a proportional limit representative of the material free from casting and rolling strains, that is, more nearly in the condition in which the material will be after a short service period. Perhaps, we may thus find some relationship between the fatigue limit in repeated bending and the static test results.

MR. H. W. GILLETT.—The term "scatter" has been in use by Mr. Upton at Cornell for years.

Mr. Gillett.

Micrographic examination for structure was made on many specimens, but did not throw sufficient light on the problem to justify inclusion of micrographs in the already long report. Other variables referred to in the report had far more effect than slight differences in microstructure.

We did not state that the Stanton test could show no correlation with endurance, if the Stanton test is made at such a small height of fall that fracture does not take place in less than say half a million blows, In other words, if you make an endurance test out of the Stanton, it would correlate with a true endurance test. But why not make a real endurance test in which the stresses can be calculated and be done with it?

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[1] Engineer, General Development Laboratory, Western Electric Co., Inc., New York City.

Mr. Gillett. In Fig. 1 presented by Mr. Lessells, instead of "energy," what is being plotted can only be denoted by the character "?", for the notch effect makes the energy applied at the base of the notch indeterminate.

Mr. Moore. MR. MOORE.—It has been proposed to use the Stanton repeated-impact test with varying energy of blow so that it may give both long-time and short-time tests. The Stanton machine operates at about 50 blows per minute; if operated faster the hammer "bounces." Fifty blows per minute means about 100,000 blows in 24 hours, or about one-fortieth the cycles of stress which can be obtained on a rotating-beam fatigue machine. If the Stanton test is to be used in the range of fatigue failure rather than failure under repeated heavy impact it will prove to be a very time-consuming test.

Mr. McAdam. MR. D. J. MCADAM, JR.—Referring to Mr. Lessells' statements about the value of repeated impact tests, I should like to confirm what Mr. Moore has just said, that the repeated impact test is not a short method for determining the endurance limit. Mr. Lessells read a paper last year before the American Society for Steel Treating in which he gave some curves plotted out to a few hundred thousand cycles. He plots them on such a scale that the curves become nearly horizontal. If he would plot them on the semi-logarithmic scale he would get a very different curve, in which there is considerable downward slope at 100,000 cycles.

Mr. Templin. MR. R. L. TEMPLIN.[1]—About two years ago there was some doubt expressed as to whether there was an endurance limit in non-ferrous materials. Shortly thereafter in the laboratory of the Aluminum Co. of America we started some long-time rotating beam tests on some heat-treated duralumin (17 S). The test specimens were cut from rolled bars, and comparatively low stresses were selected at which to run these specimens, with the idea of making sure that we were down in the region where we should find an endurance limit if there were any such thing. These tests have now been running something like a year and a half, and although the machines which are being used are showing some signs of distress, especially the motor, they have managed to keep going until this time. The tests were discussed by me last year,[2] and I should like to give some additional information, simply as a progress report on these tests, since I believe they are probably the longest time tests in this country on that kind of material. One specimen, running at a stress of 4000 lb. per sq. in., had on June 21 gone 1,311,231,000 cycles. The next specimen, 6000 lb. per sq. in., had gone 1,473,023,000 cycles, and the third one at 8000 lb. per sq. in. had gone 1,331,877,000 cycles. Our other tests on similar material, carried out in the region of one to two and three hundred million cycles, have indicated an endurance limit for this material of about 12,000 lb. per sq. in., but there were some questions which arose concerning this material and in order to make sure we started these three tests which I am reporting on at this time. **Mr. Templin.**

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[1] Chief Engineer of Tests, Aluminum Co. of America, New Kensington, Pa.

[2] Discussion on Endurance Testing of Metals, *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 126 (1923).

MR. McADAM.—I would just like to refer to one point in Mr. Gillett's paper. I haven't had a chance to study this paper thoroughly, but I note that he made one statement attributing to me the conclusion that nickel steel is better than other alloy steels. My conclusion was that in heat-treated alloy steels the endurance limit depended chiefly upon the tensile strength. I did find, however, that annealed nickel steels have a higher endurance ratio than do annealed carbon steels. **Mr. McAdam.**

A MEMBER.—Can Mr. McAdam tell us how the endurance limit of corrosion-resistant steels compares with that of other steels? **A Member.**

MR. McADAM.—The endurance ratio of austenitic corrosion-resistant steels is about the same as that of the other well-known alloy steels. The endurance ratio varies somewhat with heat treatment. Whereas for quenched-and-drawn steels it is about 0.51, for annealed steels it is about 0.48. **Mr. McAdam.**

MR. H. C. KNERR.[1]—Mr. McAdam has referred to an elastic limit and a proportional limit differing widely in value in a certain material. In the recent report of Committee E-1 on Methods of Testing these properties were considered to be identical. Mr. McAdam evidently considers that they may differ, and the same opinion seems to be held by others. An expression of Mr. McAdam's views on this subject would be of interest. **Mr. Knerr.**

MR. McADAM.—In making tension tests of corrosion-resistant steels we have found that the elastic limit may differ greatly from the proportional limit. In some specimens the proportional limit was less than one-half the elastic limit. In some non-ferrous metals also, proportional limit and elastic limit do not coincide. **Mr. McAdam.**

MR. T. McLEAN JASPER[2] (*by letter*).—It is appropriate to add a word of appreciation of the large amount of valuable information presented in these papers on fatigue. In particular it is desired to draw attention to the summary by Gillett and Mack as represented by Fig. 13 in the appropriate paper and the summary outlined by R. R. Moore and represented in Table III of his paper. **Mr. Jasper.**

In Fig. 13 referred to above is plotted a summary of the results

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[1] Metallurgist, Naval Aircraft Factory, Navy Yard, Philadelphia, Pa.

[2] Engineer of Tests, Fatigue of Metals Investigation and Research, University of Illinois.

Mr. Jasper. of fatigue tests of steel—it is presumed in flexure—from five different laboratories and using machines differing in general design at least equivalent to the varying manner in which such materials are used in engineering practice. Fig. 13 then becomes valuable to the designer in selecting his factors of safety for wrought ferrous metals when such metals are used in repeated reversed flexure. This diagram has suggested others applying the same principles to direct stress and to torsion safety factors.

In Table III referred to above the author has outlined in a concise manner specific gravity and strength ratios which become valuable to the designer of aircraft in selecting the materials most appropriate for his structure where the question of cost is subservient to the question of weight.

It may be of interest to outline the development of the use of the energy relations in determining critical points in substances. Its absolute conception is somewhat in obscurity. The mathematical equations involved were understood and available quite a long time ago. Love in his "Mathematical Theory of Elasticity" gives no reference to their development. The suggestion for their application to experimental results, as far as the writer knows, was first made by James Thompson[1] in 1849. The specific application of their use to the thermodynamic reactions in chemistry have been understood and applied for a considerable time. B. P. Haigh[2] first satisfactorily outlined their application to elastic bodies within the range of elasticity in determining static critical points, particularly with reference to the elastic limits of steel. The writer in the publication referred to by McAdam has extended their use to dynamic stressing at ordinary temperatures where various ranges of stress are applied and to static and dynamic methods of stressing at higher temperatures. The conception of the theory therefore does not belong to the writer as suggested by McAdam.

Since the publication of the paper in the *Philosophical Magazine* on the constant energy relations, additional tests on fatigue ranges are available in the most recent publication from the Fatigue of Metals Laboratory at the University of Illinois,[3] which is obtainable on request.

The tests referred to are on range values of endurance limits for repeated flexure, repeated direct stress and repeated torsion. The

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[1] J. Thompson, *Transactions*, Royal Soc., Edinburgh, 1849; *Proceedings*, Royal Soc., London, 1861.

[2] B. P. Haigh, Report on Complex Stress Distributions, British Association, 1921; and several other publications on the matter.

[3] H. F. Moore and T. M. Jasper, "Investigation of the Fatigue of Metals," series of 1923, ***Bulletin No. 142***, Engineering Experiment Station, University of Illinois.

Mr. Jasper. accompanying Figs. 3 and 4 show the results plotted on the constant energy diagram using 100 per cent as the complete reversal endurance limit of several different materials and stressed in the manner indicated by the key to the figures. The energy diagram is shown as the continuous line and the experimental values as particular points according to the key referred to above. In Figs. 3 and 4, the constant

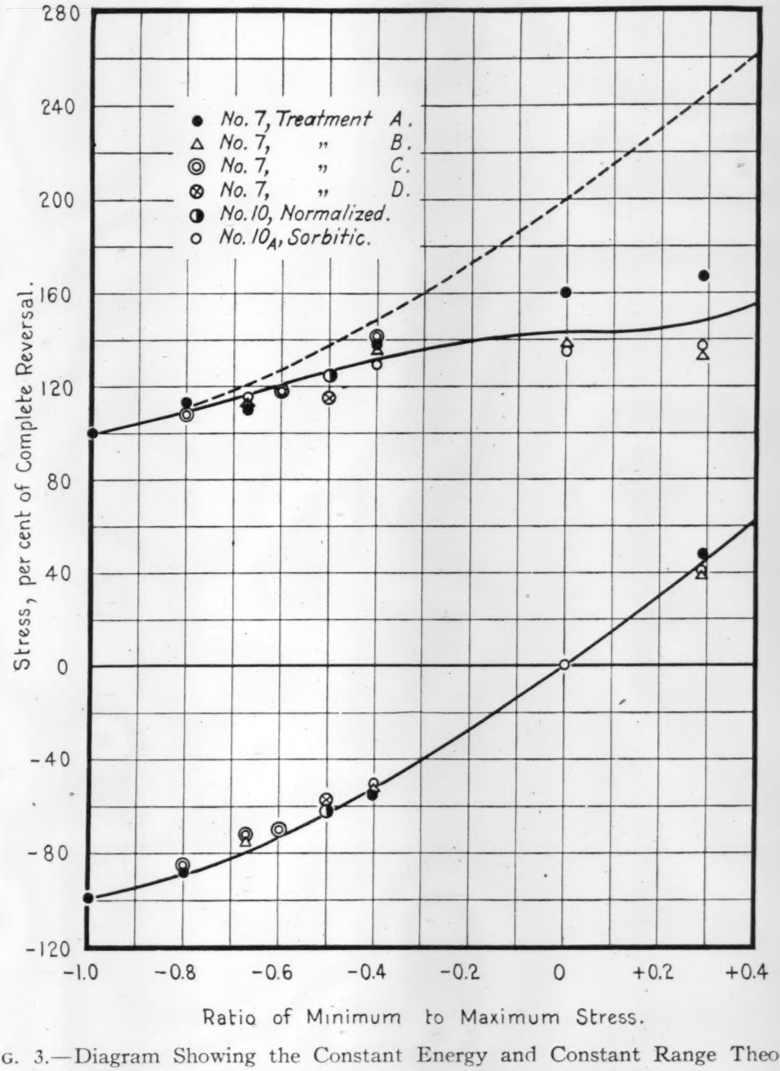

FIG. 3.—Diagram Showing the Constant Energy and Constant Range Theories with Experimental Fatigue Results of Flexure Tests Plotted.

Mr. Jasper. range diagram advocated by McAdam has been plotted. A dotted line is used for the upper limit and the continuous line of the energy diagram has been used as the lower limit.

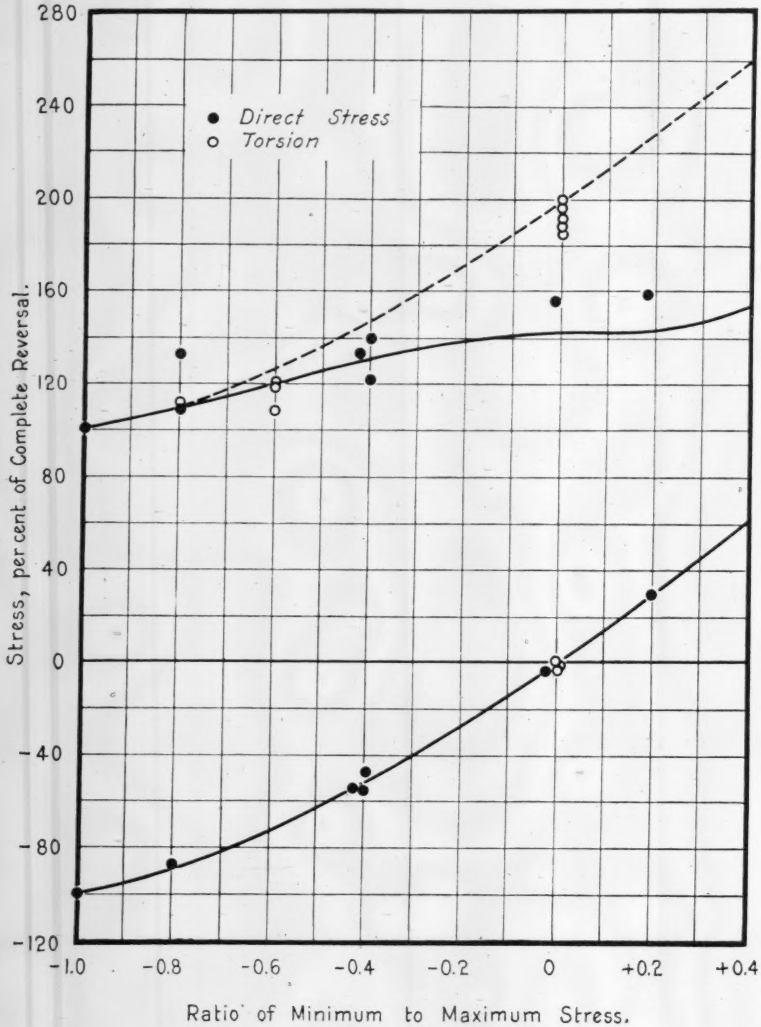

FIG. 4.—Diagram Showing the Constant Energy and Constant Range Theories with Experimental Fatigue Results in Direct Stress and Torsion Plotted.

In Figs. 3 and 4, only that portion of the energy diagram has been plotted which is useful in most elastic materials where the tension values of stress are progressively increased. The portion to the left where the compression values of stress are progressively increased have very few experimental values available and reference can be made to Fig. 1 of the original paper for those available to the writer. **Mr. Jasper.**

In Fig. 3 the results of range tests in flexure are plotted and in Fig. 4 the results of range tests in direct stress and torsion are plotted. The results for the 3.5-per-cent nickel, Series A, B and C, and for the 53-per-cent carbon sorbitic series are taken from pages 76 and 77 of *Bulletin No. 136* of the Engineering Experiment Station of the University of Illinois and the results from 3.5-per-cent nickel, Series D, and for 53-per-cent carbon normalized are taken from page 72 of *Bulletin No. 142* of the above Station. Results of B. P. Haigh's experiments as used in the paper as referred to by McAdam are plotted in Fig. 4.

From a study of Figs. 3 and 4 it would seem that the constant range idea of McAdam does not hold when steels are tested in fatigue where the ratio of maximum to minimum stress is a variable factor. For both the torsion results obtained at the University of Illinois, and by McAdam the range at zero ratio as shown by Fig. 4 is very nearly the same as for complete reversal. This fact has evidently been used by McAdam in drawing his conclusions.

In none of the experimental results plotted on Figs. 3 and 4 have the maximum stresses exceeded the static yield point of the materials tested except in the case of the torsional results. In only one case have the remainder exceeded the proportional elastic limit of the materials tested and that only in a ductile steel. This is in Fig. 4. Criticism is made of the fact that the writer in his original paper in the *Philosophical Magazine* used values which were near the yield point of the materials plotted, and yet it must be pointed out that McAdam in the presentation of his paper emphasizes the fact that ductile steels have their strength materially increased by alternating stress in fatigue. The material referred to was a ductile steel. The criticism therefore would seem inconsistent. As a matter of fact, experimental results in *Bulletin No. 142* referred to above show that in some cases mechanical work due to fatigue will increase the endurance limit 25 per cent above what a material could withstand in its virgin condition.

In conclusion it must be pointed out that in using the energy relations in anticipating the fatigue strength of a material at various ranges of stress, much the safer result is obtained than by using the constant range idea of McAdam. Although as McAdam points out, the constant energy relations are not conclusively proved, they however apply in a reasonably safe manner not only to fatigue values of varying range of stress, but to fatigue values so far obtained at the

Mr. Jasper. University of Illinois on steel at higher temperatures for a considerable temperature variation and also to static values of strength at higher temperatures obtained at other laboratories.

Mr. McAdam. MR. MCADAM (*Author's closure by letter*).—My understanding was that Mr. Jasper was the first to suggest a constant energy relationship for varying positions of the endurance range. In this understanding I believe I was not mistaken.

In his discussion Jasper refers to additional data obtained at the University of Illinois and published in a recent bulletin.[1] He presents two additional figures presumably for the purpose of illustrating these additional data. Examination of Fig. 3 of his discussion, however, shows that all the points representing experimental results with a combination of rotating bend and tension are from the preceding Bulletin which I have already discussed in my paper. The apparent reason for the omission from Fig. 3 of any results given in the more recent bulletin is that none of these new results of experiments with combination of rotating bend and tension would throw any light on the variation of the endurance range within the elastic range. The elastic ratios of the steels listed in the first division of page 72 of the new Bulletin are so low that the position of the endurance range can be varied only slightly without exceeding the limits of the elastic range.

If the static yield points of the steels are marked in the margin of Fig. 3 of Mr. Jasper's discussion, it will be noted that the experimental points near the right of Fig. 3 are not far below the corresponding yield points. Since the actual stresses, as Moore and Jasper admit, may have been 10 per cent higher than the recorded stresses, it is quite possible that the six experimental points on the right-hand side of Fig. 3 should be moved up above the corresponding yield points. I do not regard Fig. 3, therefore, as conclusive evidence of variation of the endurance range with its position within the elastic range.

Jasper's Fig. 4 gives some results that confirm the conclusions expressed in my paper, that in torsion at least the endurance range varies not more than about 5 per cent with variation of its position within the elastic range. Fig. 4 contains no additional results from the new Bulletin.

I do not understand Jasper's statement that "from a study of Figs. 3 and 4 it would seem that the constant range idea does not hold when steels are tested in fatigue where the ratio of maximum to minimum stress is a variable factor." It seems to me that Fig. 4 shows definitely that the "constant range idea" does hold for repeated tor-

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[1] *Bulletin No. 142*, Engineering Experiment Station, University of Illinois.

Mr. McAdam

sion. It also seems to me that Figs. 3 and 4 do not conclusively prove that the constant range idea does not hold for repeated tension, compression or repeated bend.

In all the experiments on variation of the endurance range described by Moore and Jasper, and in my paper, the position of the endurance range has been held constant throughout a test of any specimen. This was the proper procedure. Recently, however, I have made experiments in which the endurance range in torsion has been shifted repeatedly from one end of the elastic range to the other. Such specimens have endured about ten million cycles without failure, though the stress range of rapid frequency was only about 5 per cent less than the alternation endurance range. Under such conditions the specimen would eventually fail, however, due to the cycle of low frequency and large amplitude caused by the shifting of the range. When in any machinery part the usual range of stress shifts its position frequently, the cycle of larger amplitude due to this shifting should be considered the stress range.

Jasper's argument that because ductile materials have their endurance limits raised by gradually increasing the stress range, the endurance range of a ductile metal should not be affected by its position with reference to the elastic range does not appear logical.

Jasper in his closing paragraph emphasizes the "safety" of the constant energy formula. Not the safety but the truth of a theory, however, is of first importance. The constant energy theory as applied to repeated torsion, though safe, is not true. I believe it is better that theories and formulas for endurance properties of metals be stated in accordance with the results of experiment and that factors of safety be left to the designing engineer. Jasper applies a factor of safety of about $\frac{3}{2}$ to the definitely established relationship for repeated torsion endurance range and does not apply such a factor to his formula for the tension-compression or repeated bend endurance range.

It is of both theoretical and practical importance that it be definitely established whether or not the constant range relationship applies in tension-compression and rotating bend as it does in repeated torsion.

HIGH TENSILE STRENGTHS WITH LOW-CARBON STEELS

By Roy H. Smith[1]

While steel containing not over 0.15 per cent of carbon responds but feebly to the usual methods of quenching, it stages a rather remarkable performance when the conditions of this quench are accurately controlled; and it is rapidly and drastically done. To illustrate and describe these reactions is the purpose of this paper, which is submitted with no claim to finality of result, but as a progress report. The tests made and the data collected are not complete and are not sufficient from which to draw broad conclusions, but they point to the probability that, roughly speaking, the strength of low-carbon (0.15 per cent and under) steel, when rapidly quenched from points above 900° F. (500° C.), varies directly with the temperature. The continuity of the increase in strength is accelerated at the upper and lower critical temperature. The tests for plotting the curves are limited in number to about one hundred, but the results have been practicalized by many hundreds of tests. Many million bolts have been heat treated to meet certain of the strengths indicated by the curves.

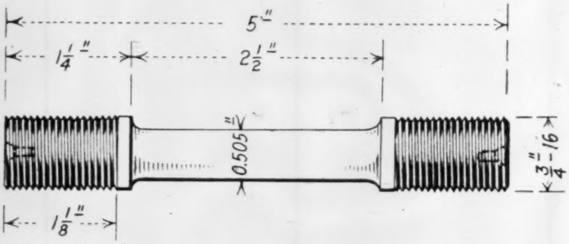

Fig. 1.—Test Specimen.

For the present tests, specimens as shown in Fig. 1 were used. For the curves in Fig. 3 they were turned about 0.020 in. larger than standard, heat treated and then ground to size. For Fig. 4 they were ground to size before treating.

The device for cooling is shown in Fig. 2. The necessity of using huge volumes of water cannot be emphasized too strongly. In place of the $2\frac{1}{2}$-in. pipe shown in Fig. 2, a $1\frac{1}{2}$-in. pipe was first tried but proved too small for uniform results.

For heating the specimens for the curves of Fig. 3 a natural gas muffle furnace was used. For those of Fig. 4 a lead pot heated by a Leeds & Northrup Electric Furnace was used; the control of temperature was, therefore, very close. The temperature was measured with a Leeds & Northrup portable potentiometer.

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[1] Vice-President, The Lamson and Sessions Co., Kent, Ohio.

Each point on the curve of Fig. 3 represents one test, each point in Fig. 4, the average of three tests. The time of heating varied from four minutes at 2300° F. to twenty-five minutes at the lowest temperature range, and an effort was made to quench just as soon as the required temperature was reached. The specimens which were normalized before treating are so marked in Fig. 3. All specimens in Fig. 4 were normalized. No connection between the normalizing and subsequent response to heat treating could be traced except at the lower temperatures. All the test specimens of Fig. 3 were made from one bar, the analysis of which was determined from the turnings. In addition specimens Nos. 455 and 499 were sent to two testing laboratories, designated Laboratories A and B (one end of each bar to each laboratory). The analyses agree as follows:

	LABORATORY A[a]	LABORATORY B[b]	LABORATORY C[c]	AVERAGE
Carbon, per cent	0.086	0.095	0.09	0.090
Manganese, per cent	0.45	0.390	....	0.420
Phosphorus, per cent	0.010	0.006	....	0.008
Sulfur, per cent	0.033	0.025	....	0.029

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[a] James H. Herron Co., Cleveland, Ohio.

[b] Pittsburgh Testing Laboratories.

[c] Lamson and Sessions Co.

All specimens for Fig. 4 were likewise made from one bar, the analysis being as follows:

Carbon	0.13 per cent
Manganese	0.51 per cent
Phosphorus	0.010 per cent
Sulfur	0.043 per cent

The present-day danger that small quantities of chromium, vanadium, tungsten or nickel might be found in commercial low-carbon steel was recognized and an especial effort made to detect these substances. No trace was indicated. This was probably an unnecessary precaution when it is recalled that we have treated such large numbers of bolts from all kinds of commercial low-carbon steel.

In taking the specimen shown in Fig. 1 from the furnace with a pair of tongs and placing in the jig, Fig. 2, then turning on the water supply, an appreciable time elapsed which apparently affects the results at all temperatures but more particularly at the higher temperatures. Partially to overcome this trouble, a $\frac{1}{4}$-in. hole was tapped in the end of each specimen for Fig. 4 and the specimens were withdrawn from the furnace with a $\frac{1}{4}$-in. rod instead of with tongs. The jig, Fig. 2, consists of a $2\frac{1}{2}$-in. pipe on the end of which is a 6-in. tee shown at *A*. A bushing, *B*, is provided with thirty-six $\frac{5}{16}$-in. holes. The heated specimens were placed in the jig as shown, supported in the center by light wires. The valve at *C* is a straightway valve, which, with a slight motion, is fully opened, letting an instantaneous flow of water to the specimen.

One of the noteworthy results of our test is the shape of the reduction-of-area curve as shown in Figs. 3 and 4; also the increase in tensile strength below the lower critical temperature. The elongation-in-2-in. curve is not shown but is roughly comparable to the reduction of area. The very marked drop in reduction of area around 1310° F. is apparently well established by the tests.

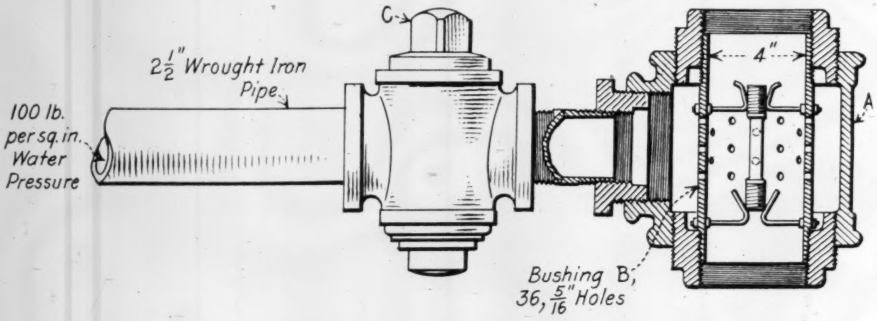

C
$2\frac{1}{2}$" Wrought Iron Pipe
100 lb. per sq. in. Water Pressure
4"
A
Bushing B; 36, $\frac{5}{16}$" Holes

FIG. 2.—Device for Cooling Specimens.

Great uniformity of results is manifest and our conclusion is that, if the specimen could be introduced into the jig more quickly and the water reach it more nearly instantaneously, no appreciable variation in tests of similar steel would occur.

An interesting check on the reliability of our results was made through the kindness of Mr. Robert R. Abbott, Metallurgical Engineer, The Peerless Motor Car Co., Cleveland, Ohio. For this check test we used five separate bars about three feet long from five different heats, turning a test specimen on each end of each bar. Bar No. 1 had specimen No. 11 on one end and No. 12 on the other end. Similarly, bar No. 2 had specimens Nos. 21 and 22. We heat treated the even numbers (12, 22, 32, 42 and 52) at the temperatures shown on the chart, and his engineers heat treated the other end, that is the odd numbers (11, 21, 31, 41 and 51) at the so-called ideal temperature for these analyses. The five results of his treatment are enclosed in the circle, and all were between 75,000 and 78,000 lb. per sq. in. tensile

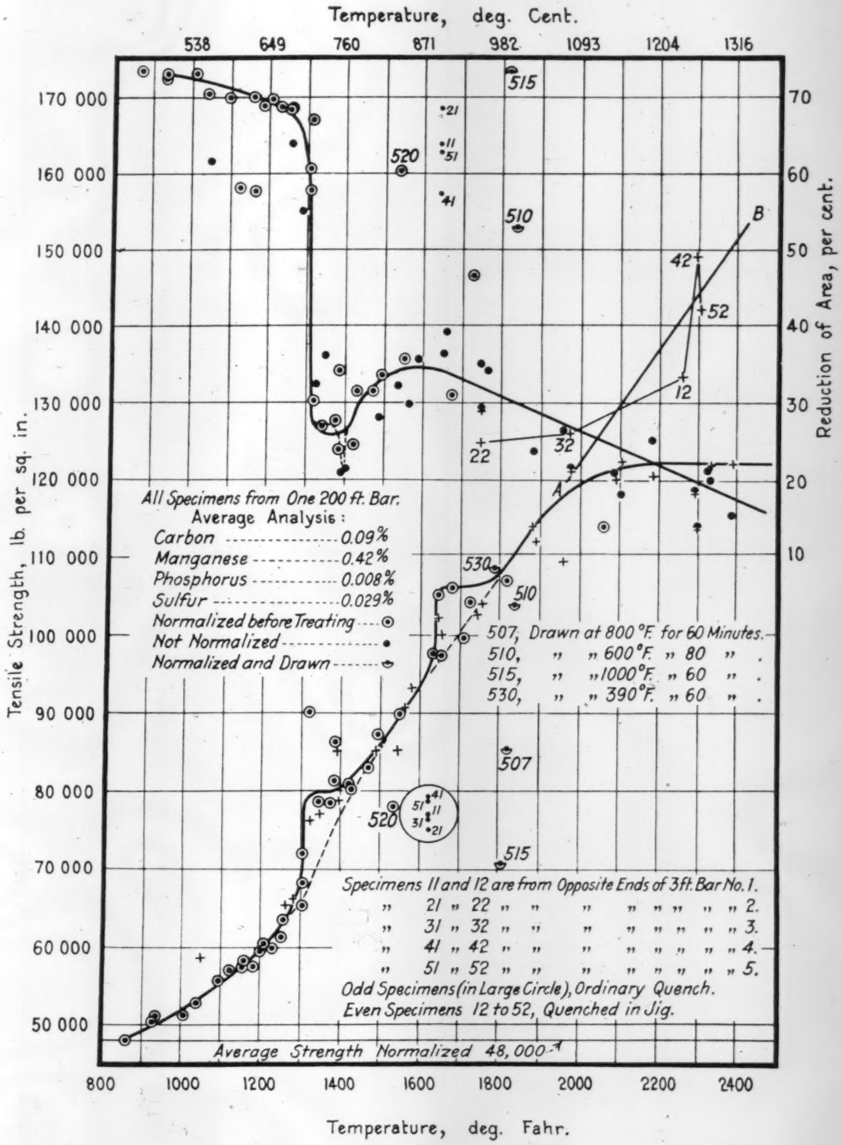


FIG. 3.—Results of Tension Tests with Low-Carbon Steels.

strength. By increasing the temperature of our specimen No. 22 about 100° F. over its mate 21 and quenching rapidly, the tensile strength was increased from 75,000 to 123,000 lb. per sq. in. Specimens Nos. 11 and 12, and 41 and 42 are high in sulfur, with carbon about 0.12 per cent and sulfur about 0.162 per cent.

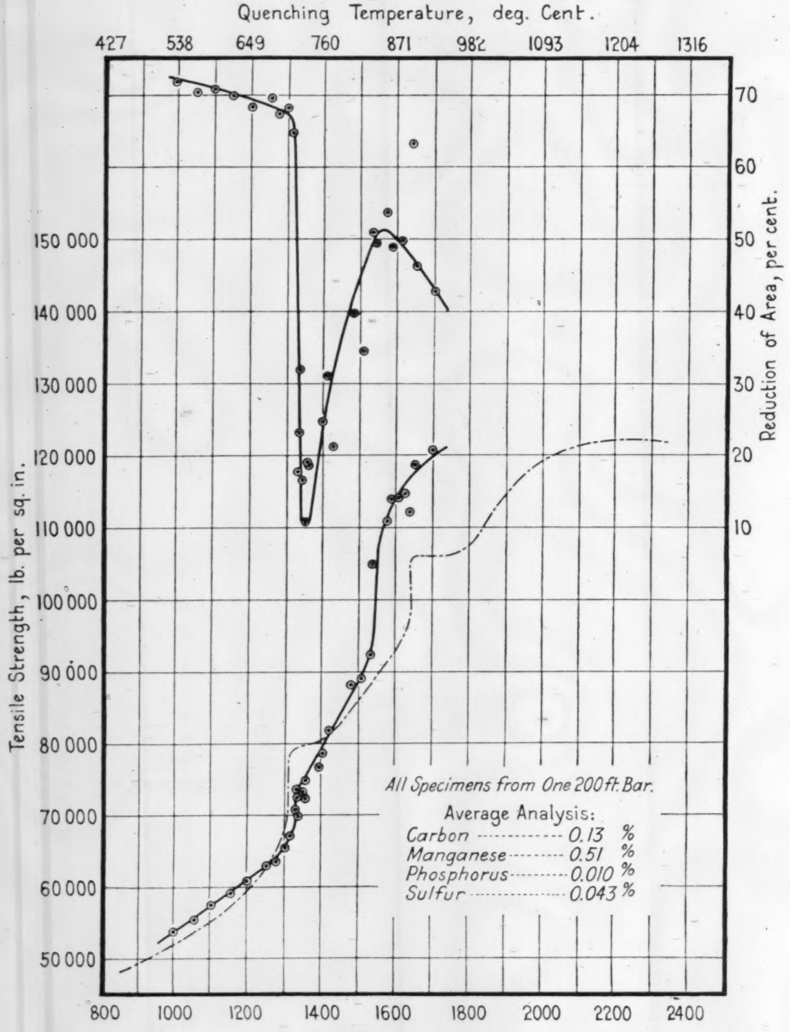


FIG. 4.—Results of Tension Tests with Low-Carbon Steels.

It is seen from the curves for tensile strength, Figs. 3 and 4, that the strength goes up in practically a straight line at the lower temperatures until about 1300° F., at which point it rises abruptly, with another marked rise around 1600° F. With our method we could not get the ordinary specimens to show uniformly and consistently above 122,000 lb. per sq. in. at the higher temperature. With the five specimens which we treated and which were attached to the 3-ft. bar, thus lending themselves to quick handling in the withdrawal from the furnace, the strength ran as high as 148,000 lb. Judging from these samples and from the further fact that we frequently have bolts in our commercial treating run from 120,000 to 140,000 lb., it is probable that the true curve instead of flattening out as it passes 1900° F. should continue as we have shown from *A* to *B* in Fig. 3. We have had bolts test as high as 160,000 lb. per sq. in. under extremely favorable conditions.

It is worth while to note in particular samples 507, 510, 515 and 530. Sample 507 was heated to 1820° F., quenched, then drawn at 800° F. for one hour. It showed 85,306 lb. per sq. in. tensile strength, but we could not gage the reduction of area due to the fact that it broke too near the shoulder.

Sample 510, quenched at 1835° F., drawn at 600° F. for 80 minutes, showed 104,000 lb. and a reduction of area of 52.8 per cent.

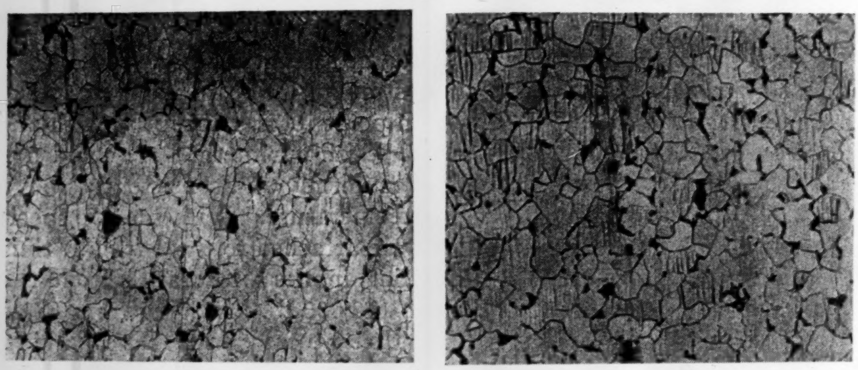
Sample 515, heated to 1810° F., quenched, then drawn at 1000° F. for one hour, showed 70,500 lb. and a reduction of area of 73.1 per cent.

Sample 530, heated to 1785° F., quenched, and drawn at 390° F. for 60 minutes, showed a strength of 108,500 lb. It broke too near the shoulder to measure the reduction of area.

In other words, it is clearly possible to produce a rivet, for example, with a high tensile strength and still retain very excellent cold riveting qualities.

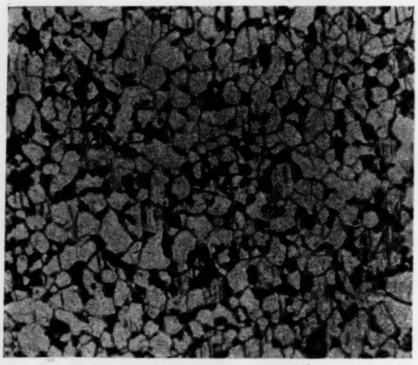
Fig. 5 shows micrographs of several samples after heat treating and after breaking. We selected sections which showed minimum straining. The data as to treatment are given under each micrograph.

It is worth while to note that the first quenching jig which we made had holes through the bushing covering a linear distance equal to the over-all length of the specimen. Practically 100 per cent of the test specimens so quenched broke at the shoulder. With a new bushing and limiting the orifices to the length of the reduced portion of the specimen, in other words to about 2 in., the break uniformly occurred in the middle third.

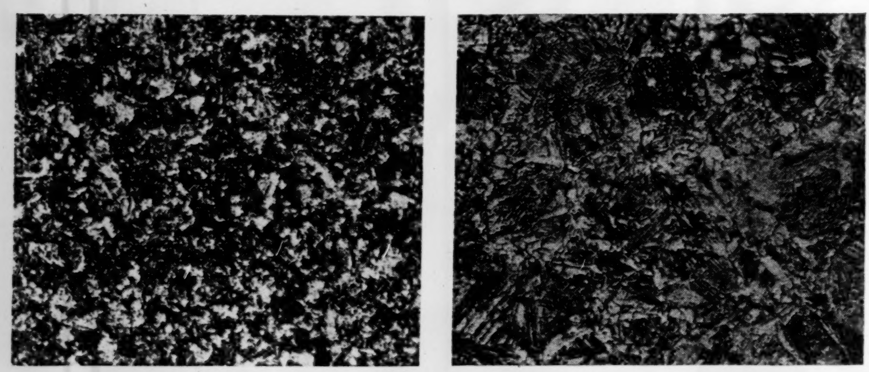


(*a*) Specimen No. 493, Normalized. Strength, 47,800 lb. per sq. in. Etched, 45 seconds.

(*b*) Specimen No. 516, Quenched from 1305° F. Strength, 71,860 lb. per sq. in. Etched, 60 seconds.



(*c*) Specimen No. 494, Quenched from 1470° F. Strength, 83,000 lb. per sq. in. Etched, 60 seconds.



(*d*) Specimen No. 491, Quenched from 1630° F. Strength, 97,670 lb. per sq. in. Etched, 60 seconds.

(*e*) Specimen No. 469, Quenched from 1890° F. Strength, 112,000 lb. per sq. in. Etched, 60 seconds.

FIG. 5.—Photomicrographs of Specimens of Low-Carbon Steel of Various Heat Treatments. Etching Solution, 5 per cent Nitol (× 100).

While the temperature of the cooling water probably has some effect, it did not have enough effect for us to measure. All of the specimens shown on the curve of Fig. 3 were quenched with temperature of cooling water about 57° F., and those of Fig. 4 at 63° F., but we uniformly secure good results in regular commercial work with water of higher temperature.

Conclusions.—The results of these experiments show that the tensile strength is increased continuously from about 48,000 lb. per sq. in. with a quenching temperature of 860° F. to about 150,000 lb. per sq. in. with a quenching temperature of 2400° F. The reduction of area decreases suddenly at the lower critical temperature. It seems well established from the tests and from our practical experience that the strengths indicated by the curves at the various temperatures can be secured and fairly well maintained in practical commercial or tonnage production without objectionable brittleness.

A wide choice in relation between the tensile strength and the reduction of area is possible by properly coordinating the heat treating and the drawing temperatures. For example, it is possible to make a rivet or bolt with a tensile strength of 100,000 lb. per sq. in. with a reduction of area of more than 50 per cent. Similarly, a tensile strength of 70,000 lb. with a reduction of area of more than 70 per cent is practicable.

The results, except at the two critical temperatures, are also consistent with Howe's statements: "In case of low-carbon steel the tensile strength seems to increase with rapidity of cooling without limit,"[1] and "As the rapidity of cooling increases, so does the tensile strength increase continuously, and the ductility decrease but more suddenly."[2] I have not found other writers to emphasize these characteristics of low-carbon steel, and apparently no commercial or practical use has heretofore been made of them.

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[1] "Iron, Steel and Other Alloys," p. 221 (1906).

[2] *Ibid.*, p. 225.

COMPOSITION AND PHYSICAL PROPERTIES OF CAST 12-PER-CENT MANGANESE STEEL

By John H. Hall[1] and G. R. Hanks[2]

Manufacture

Manganese steel, as usually made, shows the following analysis:

Carbon, per cent	Silicon, per cent	Manganese, per cent	Sulfur, per cent	Phosphorus, per cent
1.00 – 1.40	0.3 – 0.8	11.0 – 14.0	0.01	0.06 – 0.10

To secure metal of this composition, about five parts of molten low-carbon steel and one part of molten 80-per-cent ferro-manganese are mixed in a ladle; the ferro-manganese contains the proper amounts of carbon and manganese to bring those elements in the resulting steel to the desired proportions. The necessary low-carbon steel may be prepared in a bessemer converter, either bottom blown or side blown, in an open-hearth furnace, or in an electric furnace. The large manganese addition so thoroughly deoxidizes the low-carbon steel with which it is mixed that there is no discernible difference between the quality of manganese steel made from open-hearth, converter or electric-furnace metal, whatever may be the superiority of ordinary carbon or alloy steels made by one or another of these several methods.

The electric furnace, therefore, is used by makers of manganese steel chiefly to remelt foundry scrap and defective or worn-out castings with little or no loss of the manganese, which would practically all be lost if the scrap were remelted in an open-hearth furnace or used as part of the cupola charge in converter practice. The manganese steel scrap, of course, may make up the entire charge of the furnace, or form a part only, depending upon the amount available.

The phosphorus content of commercial 80-per-cent ferro-manganese being generally from 0.2 to 0.3 per cent, low-phosphorus pig iron and steel scrap have to be used for the charge of the bessemer converter or acid open-hearth furnace in order to keep the phosphorus content of the manganese steel produced within proper limits. If a basic open-hearth furnace or a basic-lined electric furnace is used the phosphorus can, of course, be reduced to the desired point before mixing the ferro-manganese and the low-carbon steel, provided no manganese steel scrap is included in the charge. If manganese were present in the furnace bath in considerable amounts, it would all be oxidized and slagged during the removal of the phosphorus. For this reason de-phosphorizing is not even attempted in making manganese steel in the electric furnace, when manganese steel scrap forms any part of the charge.

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[1] Metallurgical Engineer, Taylor-Wharton Iron and Steel Co.

[2] Superintendent, Taylor-Wharton Iron and Steel Co.

Our tests show that phosphorus in excess of 0.125 per cent lowers the strength and decreases the toughness of the steel. The phosphorus, therefore, is kept below 0.10 per cent, but for the reasons given above it is not commercially feasible to produce manganese steel with phosphorus below 0.06 per cent, and as it is necessary for reasons of economy to remelt the foundry scrap each day, the phosphorus in the steel usually varies from 0.075 to 0.095 per cent.

Sulfur is not a problem in the manufacture of manganese steel, as it combines with part of the manganese and is eliminated from the furnace bath or the ladle, so that it is seldom if ever present in amounts over 0.02 per cent, and manganese steel makers are not even obliged to analyze their product for sulfur, except occasionally for check.

The silicon content varies from about 0.3 to 0.8 per cent depending largely upon the amount of silicon in the ferro-manganese. Our tests show that up to at least 1 per cent, silicon has little influence upon the physical properties of the steel.

To keep the carbon below 1 per cent is impossible without using very expensive low-carbon ferro-manganese; our data indicate, too, that low-carbon manganese steels do not wear as well as the higher carbon steel ordinarily made. If the carbon is allowed to exceed about 1.40 per cent, the toughness of the steel is decreased, especially in the case of heavy castings, and with further increase of carbon the loss of toughness becomes very marked. The tendency of the heavier castings to crack in the molds or in heat treatment is much greater, too, when the carbon is high than when it is kept at about 1.15 to 1.25 per cent.

To insure proper toughness, manganese steel should contain not less than 11 per cent manganese. When the manganese exceeds 14 per cent, the carbon is usually so high that the embrittling effect of the carbon counteracts any increase of toughness due to increased manganese content, so that 14 per cent is the usual maximum for this element.

METALLOGRAPHY

In the cast condition, manganese steel consists of a ground mass of austenite, with a network and many patches and needles of manganiferous cementite. Adjacent to the cementite, the ground mass of the steel consists of martensite or troostite, so that under low-power magnification the cementite networks, patches and needles appear far wider than they really are. The shape, distribution and proportion of the various microscopic constituents, naturally, depend upon the size of the piece and the rate at which it is cooled.

Upon heating the steel to about 1060° C., all the carbon is absorbed in the austenite on crossing the cementite separation line *SE* of the iron-carbon diagram, and if the casting is then quenched in water, a pure austenitic structure is obtained, provided the piece is not of too great a section, or the carbon too high; in which case some of the carbon separates out as cementite, mostly as a network between crystals of austenite. If the steel is allowed to cool below about 800 or 850° C. before quenching, a similar microstructure is obtained; and if it is not heated hot enough or held long enough at the maximum temperature, not all the cementite will be absorbed in the austenite. Finally, if the quenched austenitic steel is reheated to about 480° C., the cementite separates out as needles and networks between austenite crystals. Any sample of manganese steel showing free cementite under the microscope will be less tough than properly treated material, the degree of inferiority depending upon the extent of the cementite separation.

PHYSICAL PROPERTIES

Tensile Properties.—As the steel is not commercially machineable and the cost of ground test bars is naturally high, tension tests in most cases are made on bars cast to shape and only rough ground for size. Naturally, surface decarburization affects the results of tests on these bars. A bar about 0.75 in. in diameter and $2\frac{1}{2}$ in. long between shoulders is frequently used. The errors inevitable in such test pieces are compensated for to some extent by multiplying the number of bars tested. The average properties of many hundreds of such bars are:

Tensile Strength	75 000 to 105 000 lb. per sq. in.
Elongation in 2 in	15 to 35 per cent
Reduction of Area	15 to 35 per cent

The yield point cannot be obtained by the drop of the beam or even by multiplying dividers, for a reason that will be discussed later. The elastic limit has been determined by extensometer in the Mechanical Engineering Laboratory of Columbia University to be about 30,000 lb. per sq. in., a figure which we use in all our designing. Fig. 1 shows the stress-strain diagram for a typical test.

Bending Tests.—Bending tests are usually carried out on cast (not ground) bars from ½ to 1 in. thick, so that the result of a bending test is dependent largely upon the degree of surface decarburization of the test bar. If it has been heated fairly rapidly and held but a short time at the maximum temperature, it will give a far better test than if it has been heated slowly and held longer at the maximum temperature, as for instance when it is treated with castings of heavy section. For this reason a test bar cast attached to a heavy casting is not representative of the quality of the steel in that casting, as the decarburized zone forms a relatively greater proportion of the cross-section of the test bar than of the casting. This, of course, applies also to bars for tension test.

In general, a bar of manganese steel ½ in. thick should bend cold 180 deg. around a 1-in. pin and a ¾-in. bar should bend cold 140 deg. around a 1-in. pin without breaking. The surface of the metal on the outside of the bend, however, will always show a number of small checks, which are formed by the failure of the decarburized outer metal. When the test bars have been treated with heavy castings, resulting in a deeper zone of decarburization, these checks cause failure of the bar, and in extreme cases a bar ¾ in. thick may fail at as low as 80 to 100 deg. bend.

Of course, test bars of approximately the same cross-section as the castings with which they are treated might be used, but they would be costly and there is as yet no information in existence as to the angles of bend they should give.

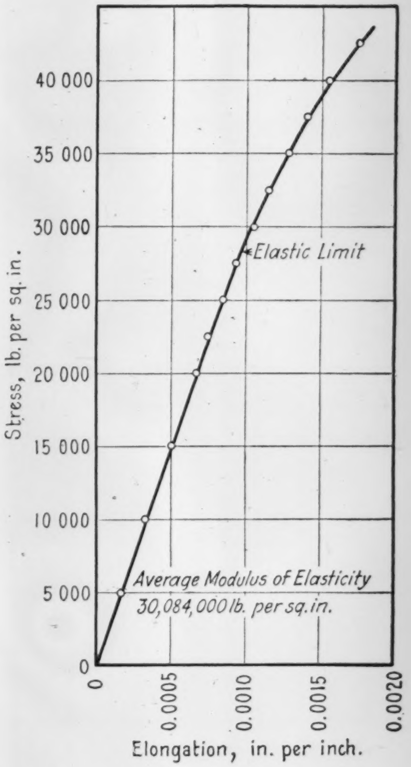

FIG. 1.—Typical Stress-Strain Diagram of Tension Test of Manganese Steel.

Shear.—The shearing strength of the metal is very high, much higher than would be expected from its low elastic limit. The reason for this high shearing strength will be discussed later. An average of many tests of 1-in. diameter cast (not machined) bars is 84,000 lb. per sq. in. in single shear.

Hardness.—The Brinell hardness of the steel in the cast and in the heat-treated condition is only moderately high, about 185 in the untreated condition and 180 to 200 after treatment. The correctness of this relatively low figure is confirmed by the fact that the steel can be dented with the peen end of a machinist's hammer, or nicked with a cold chisel, *up to a certain point.* The first blows of the hammer produce a considerable dent, but as the hammering proceeds it will be noticed that the impression produced grows smaller and smaller, and finally a point is reached where the hammer hardly mars the surface. Apparently the steel has grown much harder from the effect of the cold working; and a Brinell test upon the cold-worked surface shows that it has indeed, the hardness being about 450, instead of the 180 to 200 of the heat-treated steel. In fact, the rapidity with which this metal hardens under cold working of all kinds is extraordinary, and is probably responsible for its most valuable properties, as well as for its greatest weakness.

This is the explanation of the fact referred to above that the yield point of the steel cannot be determined by the drop of the beam or the dividers. To secure a pronounced drop of the beam, the test bar must stretch to a considerable extent with almost no increase in the applied load. When a manganese steel bar is under test, the beam hesitates and appears ready to drop, not once and pronouncedly, but repeatedly and irregularly, so that the operator finds it next to impossible to say which little drop is the true one. Similarly if multiplying dividers are used to watch the stretch more carefully, the rate of stretch is seen to increase gradually and unevenly and no particular stress can be chosen as the yield point. The reason for this is that as the bar stretches a little at any particular point in its length, the steel at that point is immediately hardened and strengthened so much that it stops stretching, and the applied stress must be raised before stretch starts at another point. As a result, stretch is distributed over the whole length of the bar until the elastic limit has been much exceeded, and necking occurs to but a limited extent.

The explanation of the high shearing strength of the steel is probably similar; shearing begins at a relatively low pressure, probably not much above the elastic limit, but the progress of the shear is resisted to a rapidly increasing extent by the hardening of the metal due to the cold working of the shearing effect, and the pressure required to produce final rupture is very high.

The non-machineability of the steel is almost certainly due to the same phenomenon, the metal hardening in front of the tool so rapidly as to wear out the tool before the cut has progressed very far; and the metal under the tool is greatly hardened, so that it is much more difficult to start the second cut than the first.

Wear.—Manganese steel almost certainly owes its power of resisting heavy abrasive wear to the property just described of hardening under cold working to an extent not approached, to the authors' knowledge, by any other ferrous metal. The late Henry M. Howe first called attention to this phenomenon in a paper before the American Institute of Mining and Metallurgical Engineers.[1] In a jaw crusher, for instance, where the steel is subjected both to heavy pressure and to severe abrasion, manganese steel will outlast from five to ten times metals whose initial hardness is much greater. Tests show that the initial rate of wear of a manganese-steel crusher jaw is somewhat greater than the rate after a few tons of stone have been crushed; this difference in the case of small crusher jaws carefully weighed being from 0.13 g. lost per square inch of jaw surface per 1000 lb. of stone crushed, for the first two tons of stone, to 0.08 g. lost per square inch of jaw surface per 1000 lb. of stone crushed, after six or eight tons had been put through. This is due, of course, to the hardening of the steel by the kneading effect of the stone crushed. Jaws of other hard steels, such as nickel, chrome, nickel-chrome, chilled iron, etc., tested at the same time in the same crusher with the same stone, showed practically no difference in the rate of wear as the test progressed, and in consequence of their high initial rate of wear and of the fact that this rate decreased little if any as the test progressed, jaws of these steels were worn out after a life, measured in terms of tons of stone crushed, of only from one-tenth to one-fifth that of manganese steel.

Singularly enough, these tests, which were carried on for some four or five years, showed little variation in the rate of wear of manganese steel due to differences in heat treatment that produced marked variations in the toughness; and the lowering of the manganese content, provided the carbon was held constant, gave not poorer but rather better results in wearing rate. The loss of toughness as the manganese content is decreased has made it impossible to take advantage of the better resistance to wear of the 6 or 8-per-cent manganese steels.

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[1] *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. LI, p. 881.

The results of these crusher tests, in summary, are as follows:

COMPOSITION, PER CENT				AVERAGE WEAR, G. PER SQ. IN. OF JAW SURFACE PER 1000 LB. OF STONE CRUSHED	
C	MN	CR	NI	FIXED JAWS	MOVING JAWS
1.25	12.0[a]	....	....	0.0719 to 0.1911	0.0832 to 0.124
0.24	1.19	....	....	1.262	1.210
0.54	0.65	....	....	0.9533	1.0709
0.26	0.55	1.23	....	1.19	0.8209
0.48	0.67	0.43	....	1.069	1.500
0.59	0.47	0.73	....	0.718	0.823
0.24	0.87	....	3.63	0.577	0.4673
0.55	0.90	....	3.29	0.432	0.4841
0.46	0.65	....	6.24	0.2361	0.2700
0.44	0.77	0.44	1.38	0.4064	0.3911

[a] Average composition.

From these results it is readily apparent that carbon steel wears about ten times as fast as, and chrome and nickel steels wear at least five or six times as fast as, manganese steel.

Turning now to wear of a different type, where the metal is not subjected to heavy pressure with its resulting cold working, we find that manganese steel does not develop the same resistance to wear as it does in crusher jaws, and in fact it may even wear out more rapidly than do the harder ferrous metals. To take an extreme case, we have found that under a sand blast, manganese steel wears as fast as plain 0.25-per-cent carbon, cast steel, and far faster than chilled iron. There are many classes of wear in which pressure is almost absent, and in such cases the abrasive action of fine particles of hard material like quartz, which cut into the surface of the steel, rapidly wears the metal away. Ridiculous as the statement may appear, a set of manganese-steel steam shovel teeth will often last several months, handling blasted rock of the hardest kind and wear out in ten days or two weeks digging into a bank of glacial clay or shale containing a large amount of quartz or other hard mineral in small particles. In the absence of the hardening effect of blows or pressure that dent and deform the steel, the resistance to wear is comparatively low; reminding one of the line in the poem in London *Punch* after Lincoln's assassination:

> "How, iron-like, his temper grew by blows."

Fatigue Resistance.—The hardening of the steel under cold working, which confers upon it an ability to resist heavy abrasive wear not equalled or even approached by any other ferrous metal, is responsible also for its greatest weakness—a low resistance to repeated stress, approaching or slightly exceeding its elastic limit. Owing to the expense of preparing test pieces, we have made no experiments with vibratory machines in which the maximum fiber stress can be accurately measured, but have contented ourselves for the present with tests made in an Olsen machine in which a $\frac{3}{4}$-in. round or square bar with a free length of 8 in. is clamped in a vise at one end and bent back and forth at the free end. With a movement of $\frac{3}{16}$ in. each way, giving a maximum fiber stress that probably slightly exceeds the elastic limit, cast manganese steel bars endured an average of from 9000 to 23,000 alternations. Heat-treated rolled nickel-steel bars of approximately 0.50 per cent carbon, 1.50 per cent nickel and 0.80 per cent chromium endured an average of 72,000 alternations, while cast steel of about 0.25 per cent carbon and 1.25 per cent manganese endured an average of 20,000 alternations when normalized and reheated, and 45,000 alternations when water-quenched and reheated.

From these results it will be seen that the resistance of manganese steel to severe alternating stresses is low; and these tests are confirmed by the failure by fatigue in service of certain castings which for one reason or another cannot be so designed as to provide suitable sections to resist the stresses imposed. The fractures of the cracked or broken pieces in these cases always show the appearance typical of failure by fatigue.

Coefficient of Expansion.—Determinations by the U. S. Bureau of Standards on cast manganese-steel bars gave a formula for the coefficient of expansion between 20 and 100° C. as follows:

$$L_t = L_o\left(1 + (16.96 \times 10^{-6}\, t) + (0.0148 \times 10^{-6}\, t^2)\right)$$

where L_t is the length at t° C. and L_o is the length at 0° C., t being given in degrees Centigrade.

Heat Conductivity.—In an article by H. R. Pennington,[1] the heat conductivity of manganese steel is given as 2.31, compared to copper at 100; or 75 michroms per centimeter cube at 15° C., which is one-seventh that of iron wire.

Electrical Conductivity.—The specific electrical resistance of manganese steel is given in Smithsonian Physical Tables, Sixth Edition, page 319, as 0.06554 against 0.0105 for bessemer steel of 0.045 per cent carbon, and 0.0108 for "Whitworth Mild Steel" of 0.09 per cent carbon.[2]

Magnetic Properties.—To all intents and purposes, manganese steel is non-magnetic, that is, it has no attraction for the magnet. If a bar of the steel be placed across an ordinary field compass, the needle will be deflected only one or two degrees. As yet very little practical use has been made of this property and for years the only application of the steel based on its non-magnetic properties was the cover plates of electric lifting magnets, in which the power of resisting wear was also of value. Of late the attention of electrical engineers has been drawn to the subject and the steel is being applied to various transformer parts and other portions of electrical machinery where a strong, non-magnetic metal is essential.

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[1] *Engineering and Contracting*, February, 1922.

[2] These figures were taken from a paper by Hopkinson in *Phil. Trans.*, Royal Soc., Vol. 176.

Determinations made of normal induction and magnetizing force gave results as follows:

INDUCTION, GAUSSES	MAGNETIZING FORCE, GILBERTS PER SQ. CM
10	9.5
20	18.4
30	27.3
50	44.8
70	62.5
100	89.3
150	136
200	183
250	231
300	279

The magnetic permeability, being the ratio of induction to magnetizing force, is nearly unity, the permeability of air, for the determinations in this table.

From Smithsonian Physical Tables, Sixth Edition, page 321, the following figures are quoted for magnetic values in intense fields, the references given being the work of Ewing:[1]

MAGNETO MOTIVE FORCE	MAGNETIC MOMENT PER CU. CM.	MAGNETIC INDUCTION	PERMEABILITY
1930	55	2620	1.36
2380	84	3430	1.44
3350	84	4400	1.31
5920	111	7310	1.24
6620	187	8970	1.35
7890	191	10290	1.30
8390	263	11690	1.39
9810	396	14790	1.51

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[1] *Phil. Trans.*, Royal Soc., 1885 and 1889.

MAGNETIC TESTS OF A.S.T.M. DRILLS

By W. B. Kouwenhoven[1]

Material

The drills used in this investigation consist of fifty-two high-speed drills, ½ in. in diameter, and numbered 1 to 52, inclusive. These drills were made by the Cleveland Twist Drill Co. and received varying heat treatments at their plant. In some cases the drills also differ in their mechanical features and in their chemical analysis. A record of all the variables was furnished by the Cleveland Twist Drill Co. and is given in Table I. The chemical compositions are as follows:

	Drills 1 to 42	Drills 46 to 52
Carbon	0.63 per cent	0.60 per cent
Manganese	0.20 per cent	0.19 per cent
Silicon	0.23 per cent	0.13 per cent
Chromium	3.98 per cent	3.42 per cent
Tungsten	17.66 per cent	18.55 per cent
Vanadium	0.85 per cent	0.86 per cent

Methods of Test

Several methods were employed in making the magnetic tests of the drills, but only two will be mentioned here, namely, a Direct Current Permeameter Method and an Alternating Current Comparison Method. Magnetic tests of the drills were made by the last-mentioned method at both 60 and 10 cycles. The A.C. comparison method was developed and the special apparatus for the test was constructed by the author, who also carried out the measurements at 60 cycles in the Electrical Engineering Laboratories of the John Hopkins University. The tests at 10 cycles were made by Mr. Thomas Spooner in the laboratories of the Westinghouse Electric and Manufacturing Co. using the special apparatus mentioned above. Mr. Spooner also measured the iron losses in the drills at 10 cycles using a wattmeter. The ohmic resistance of the drills was also measured.

Hardness and drilling tests were made by Mr. Emmons of the Cleveland Twist Drill Co.

Magnetic Tests

The object of the magnetic tests was to determine if it is possible to classify the drills magnetically in accordance with their heat treatments and other features, and to determine by magnetic analysis

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[1] Associate Professor, Department of Engineering, Johns Hopkins University.

TABLE I.—RECORD OF VARIABLES OF ½-IN. HIGH-SPEED TAPER SHANK DRILLS FOR THE A.S.T.M. MAGNETIC TEST.

Drill	Remarks	Heat Treatment		Quenching Designation
		Quenching Temperature, deg. Fahr.	Drawn at — deg. Fahr.	
No. 1	Mechanically Regular	2000	....	A
No. 2	Mechanically Regular	2000	450	A
No. 3	Mechanically Regular	2000	1050	A
No. 4	Mechanically Regular	2000	1200	A
No. 5	Mechanically Regular	2200	....	B
No. 6	Mechanically Regular	2200	450	B
No. 7	Mechanically Regular	2200	1050	B
No. 8	Mechanically Regular	2200	1200	B
No. 9	Mechanically Regular	2350	....	C
No. 10	Mechanically Regular	2350	450	C
No. 11	Mechanically Regular	2350	1000	C
No. 12	Mechanically Regular	2350	1050	C
No. 13	Mechanically Regular	2350	1100	C
No. 14	Mechanically Regular	2350	1200	C
No. 15	Broken			
No. 16	Mechanically Regular	2400	450	D
No. 17	Mechanically Regular	2400	1050	D
No. 18	Mechanically Regular	2400	1200	D
No. 19	Mechanically Regular	2450	....	E
No. 20	Mechanically Regular	2450	450	E
No. 21	Mechanically Regular	2450	1050	E
No. 22	Mechanically Regular	2450	1200	E
No. 23	Mechanically Regular	Unhardened		
No. 24	Mechanically Regular	1450 in water	450	
No. 25	Mechanically Regular	Quenched at 2350° F. twice without annealing between and drawn to 450° F.		
No. 26	Mechanically Regular	Quenched at 2350° F. twice, annealed between quenchings at 1435° F. and drawn to 450° F.		
No. 27	Mechanically Regular	In open fire, light sweat heat, 450° F.		F[a]
No. 28	Mechanically Regular	In open fire, light sweat heat, 1050° F.		F[a]
No. 29	Mechanically Regular	In open fire, light sweat heat, 1200° F.		F[a]
No. 30	Mechanically Regular	2350, Soak 3 min. at heat	450	G
No. 31	Mechanically Regular	2350, Soak 3 min. at heat	1000	G
No. 32	Mechanically Regular	2350, Soak 3 min. at heat	1050	G
No. 33	Mechanically Regular	2350, Soak 3 min. at heat	1100	G
No. 34	Regular flutes; regular web clearance; 0.005 in. over size	2350	450	
No. 35	Missing			
No. 36	Narrow flutes; thick web; wide margins shallow, clearance	2350	450	
No. 37	Regular flutes; thick web; regular clearance	2350	450	
No. 38	Regular flutes; thin web; regular clearance	2350	450	
No. 39	Wide paragon style flutes; regular paragon web	2350	450	
No. 40	Wide paragon style flutes; thin web narrow margin; deep clearance	2350	450	
No. 41	Regular flutes; regular web; light ground clearance	2350	450	
No. 42	Regular flutes; regular web; heavy milled clearance 0.025 to 0.030 in. on each side	2350	450	
No. 43	Carbon steel drill	1435 in water	450	
No. 44	Carbon steel drill	2200 in oil	450	
No. 45	Carbon steel drill	Unhardened		
No. 46	Analysis No. 8237; Mechanically Regular	2200	450	H
No. 47	Analysis No. 8237; Mechanically Regular	2200	1050	H
No. 48	Analysis No. 8237; Mechanically Regular	2350	450	I
No. 49	Analysis No. 8237; Mechanically Regular	2350	1050	I
No. 50	Analysis No. 8237; Mechanically Regular	2350	1200	I
No. 51	Analysis No. 8237; Mechanically Regular	2400	450	J
No. 52	Analysis No. 8237; Mechanically Regular	2400	1050	J

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[a] These drills were hardened without pyrometric control according to a widely used practical method based on the observation of the melting of the film of oxide on the tool. The temperature approximates 2350° F.

those drills which had been properly heat treated. As mentioned above, different magnetic tests were tried in order to determine the best and simplest test for comparing the drills magnetically.

The drills were somewhat difficult to test magnetically on account of their shape which made it hard to obtain uniform contact with the yokes of the permeameter. However, if care was used in placing the drills in the permeameter, the results could be checked.

DIRECT CURRENT PERMEAMETER

Permeameter.—A special permeameter was constructed for this work. It was made of laminated sheet silicon steel, 0.014 in. thick, in accordance with previous designs that had worked successfully in commercial work and investigations. A sketch showing the construction of the permeameter is given in Fig. 1. The cross-sectional area of the yoke was about 6.5 sq. cm.

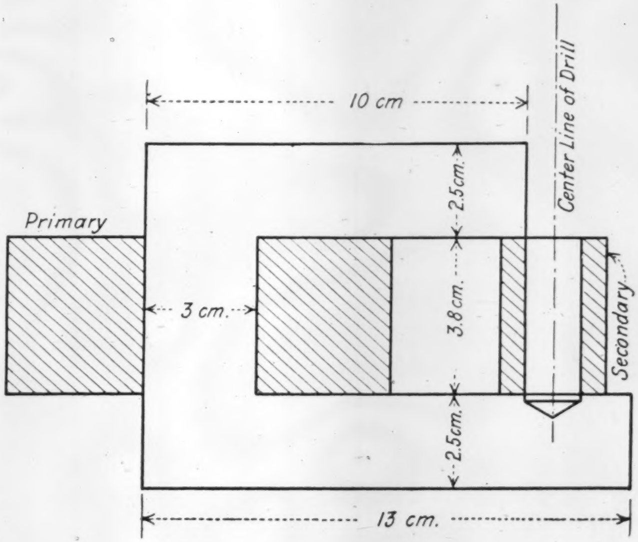

FIG. 1.—D. C. Permeameter.

The secondary coil used to measure the flux in the drill consisted of 355 turns of wire of No. 24 B. & S. gage wound on a thin fiber tube 3.8 cm. long. Only the lower or cutting end of the drill was encircled by this coil. The magnetizing force was not measured, but was adjusted to such a value as to give approximately 10,000 maxwells per sq. cm. in the average drill. The magnetizing current was maintained constant throughout the test at 7.0 amperes.

Operation.—The method of reversals was used, and B_m, the maximum flux density for the given magnetizing force was determined in the usual manner. The residual magnetic flux density, B_r, was found by opening the magnetizing current circuit and noting the deflection. B_r was then calculated in accordance with standard practice.

The coercive force, H_c, was determined for drill No. 12 which was taken as a standard. The value of the demagnetizing current necessary to reduce the flux in this drill to zero was measured and found to equal 2.8 amperes. This same demagnetizing current was applied to all of the other drills, and the galvanometer deflections noted. From these deflections was calculated a factor called B_c, the flux corresponding to the coercive force of the standard sample. In the method of reversals the proper value of the coercive force is obtained when the galvanometer deflection equals one-half the B_m deflection found for the given magnetizing force. If the deflection for a standard demagnetizing current is less than one-half the B_m reading, then the flux in the sample is not reduced to zero and the sample is harder magnetically than the standard. If the deflection is greater than one-half the B_m reading, then the standard demagnetizing force used is too large, the flux is carried beyond zero to some value in the opposite direction and the sample is softer magnetically than the standard.

The factor B_c is determined by doubling the galvanometer deflection obtained by applying to the drill under test the demagnetizing current found for drill No. 12, which was chosen as a standard. This doubled deflection is then compared to the B_m deflection for the given drill. If the doubled deflection is less than the B_m reading, the difference is written with a positive sign showing that the drill under test is harder magnetically; if the doubled deflection is greater than the B_m reading then the difference is written with a minus sign showing that the drill under investigation is softer magnetically.

Previous tests and investigations have shown that this factor B_c may be used as a measure of the magnetic hardness of a sample. Its determination requires less time than that needed for finding the actual coercive force.

ALTERNATING CURRENT COMPARISON METHOD

In order to reduce if possible the time required for the magnetic tests, alternating current was tried. A comparison method was developed which gave satisfactory results.

Apparatus.—Two small air core transformers were constructed as nearly exactly alike as possible. The core of each transformer consisted of a bakelite tube carefully turned to size. The secondary winding, consisting of 2000 turns of wire, was wound on the tube and over it a primary winding of 160 turns. The winding length was 2 in. (5.08 cm.). The secondary windings of the two transformers were carefully compared and after rewindings and adjustments the secondary coils were brought to equality. The primaries were then wound and also adjusted until alike.

The resistance of the primary windings was 0.34 ohms at room temperature. The primary current of 3.75 amperes heated up the windings so that the resistance of the primary under operating conditions averaged 0.38 ohms. The voltage drop in the primary due to resistance alone is 1.42 volts. With drill No. 12 in one of the coils, Mr. Spooner found the secondary voltage equal to 0.473 volts at 10 cycles. At 60 cycles this would amount to 2.84 volts, which, when reduced to the primary side, would equal 0.227 volts. The magnetizing force, with a primary current of 3.75 amperes, was 118 ampere turns per centimeter. When completed, the two transformers or coils were mounted and the connections arranged so that the primary windings could be connected in series or in parallel as desired. The secondaries were connected in series opposing and their resultant e.m.f. measured by an A. C. galvanometer. The galvanometer was a standard A. C. instrument of the Pyrolectric Co. The excitation of the galvanometer field coils was supplied from the wound rotor of a three-phase induction motor which was used as a phase shifter. The source of alternating current for the tests and phase shifter was a 60-cycle three-phase pure sine wave generator of special construction. The diagram of the connections used is shown in Fig. 2.

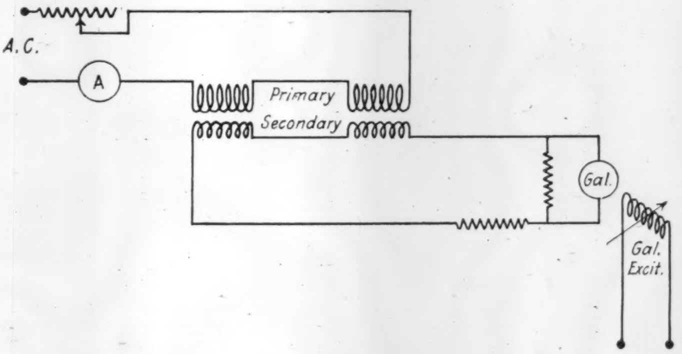

FIG. 2.—Diagram of A.C. Connections.

Operation.—In alternating current tests, readings called "B_m", "H_c A.C. Read" and "A.C. Loss" were taken at both 10 and 60 cycles. The "H_c" and "A.C. Loss" readings are affected by both the eddy current and hysteresis losses in the drills.

The A.C. "B_m" Test.—The primary windings were connected in series so that the same magnetizing current passed through each. Drill No. 12, the standard, was placed in one of the transformers and the e.m.f. induced in the secondary of that transformer was applied to the A.C. galvanometer. The phase of the galvanometer excitation was then adjusted to give maximum deflection. The simplest and most accurate method of making this phase setting is to adjust the phase of the galvanometer excitation so as to give zero deflection, and then shift the phase 90 electrical degrees, which gives the maximum deflection. The transformers' secondaries were then connected in series opposing, the other drills were placed one at a time in the other transformer and the resultant A.C. galvanometer deflections noted. These deflections are proportional to the difference between the B_m of the standard and the B_m of the sample. The phase of the galvanometer exciting current was not altered during a run. None of the drills was allowed to remain in the transformers long enough to heat.

The "H_c A.C. Read" Test.—In this test the primary windings of the transformers were connected in series and the phase of the galvanometer excitation was shifted 90 deg. from the direction used in the A.C. "B_m" test. Drill No. 12 was used as a standard and the other drills were compared with it. The readings of the galvanometer are proportional to the difference between the hysteresis and eddy current losses in the drill under test compared to those in the standard drill; both drills being subjected to the same magnetizing force. The readings are called the "H_c A.C. Read" results.

The "A.C. Loss" Test.—In this test the primary windings of the two transformers were connected in parallel and the same voltage applied to both. The phase of the galvanometer excitation was shifted 90 deg. from that used in measuring "B_m". Drill No. 12 was used as the standard and the other drills were compared with it. The readings obtained are called the "A.C. Loss" readings and are proportional to the difference between the hysteresis and eddy current losses of the drill under test and the standard.

When the transformers were constructed, this test was not considered as a possibility and, therefore, no attempt was made to make the resistance of the primary windings low. This method was first applied to the drills under the assumption that they were being magnetized to the same maximum flux density. If, however, the relative values of the resistance drop and the back e.m.f. of the primary windings is considered, this is seen to be far from true, and it is impossible, with the data available, to state what the conditions were for any given drill. It is regretted that there was not sufficient time to construct new transformers with low-resistance primary windings and to repeat this part of the test.

Theory.—The theory upon which these A.C. measurements are based is relatively simple.

On determining the A.C. "B_m" values the same current is passed through both primaries in series, and, therefore, both drills are subjected to the same magnetizing force since both transformers are identical. The voltages induced in the secondaries will be proportional to the fluxes threading their respective drills. The A.C. galvanometer is connected to measure the difference between the two voltages, and if more flux is threading the drill under test than the standard drill the deflection of the galvanometer will be in one direction, if less, in the opposite direction. The phase of the induced secondary voltage was measured for each drill, and all were found to lie in an angle of approximately 2 deg.

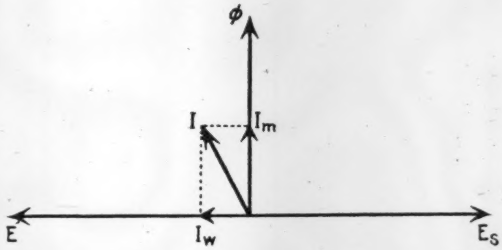

FIG. 3.—Vector Diagram of the Transformer.

The theory involved in the so-called "H_c Read" and "A.C. Loss" measurements may be easily understood from the vector diagram of the transformer shown in Fig. 3.

In Fig. 3, E_s is the secondary voltage, E the secondary voltage reversed, ϕ the magnetic flux, I_m the magnetizing component of the exciting current I, and I_w, the component of the exciting current that furnishes the losses. In measuring "B_m" the phase of the galvanometer excitation is adjusted so as to measure the flux in the direction of I_m. In the "H_c A.C. Read" and "A.C. Loss" determinations the galvanometer excitation is shifted 90 deg. to measure the loss component.

In making the 60-cycle tests the author adjusted the phase of the galvanometer field with drill No. 12 in one of the coils as mentioned above. Mr. Spooner made tests at 10 cycles using the same method of adjustment and also made loss tests setting the phase of the galvanometer field to give zero deflection when there was no drill in either coil. Mr. Spooner claims that his setting gives more accurate loss results. The readings obtained by the two methods of setting will differ in magnitude.

It is not possible to state at this time which method of adjusting the phase of the galvanometer excitation gives the more accurate loss readings. Mr. Spooner, however, obtained a better check with the wattmeter readings for his setting than for settings he made using the author's method.

TABLE II.—COMPARISON OF A.C. "B_m" AND D.C. "B_m" READINGS.

Drill	Difference from B_m of Standard, cm. deflection			Drill	Difference from B_m of Standard, cm. deflection		
	A.C., 60 cycles	A.C., 10 cycles	D.C. Flux Density		A.C., 60 cycles	A.C., 10 cycles	D.C. Flux Density
No. 1	−1.5	−0.8	−450	No. 27	−1.7	−1.2	−900
No. 2	+2.2	+2.3	+260	No. 28	0.0	+0.8	+390
No. 3	+2.1	+2.6	+910	No. 29	+5.4	+6.4	+2800
No. 4	+7.4	+8.6	+2530	No. 30	−2.6	−2.4	−1350
No. 5	−4.4	−3.9	−980	No. 31	−3.3	−2.6	−490
No. 6	−2.0	−1.9	−470	No. 32	−2.1	−1.5	−380
No. 7	−1.7	−1.2	+320	No. 33	+1.4	+2.3	+1850
No. 8	+5.7	+6.5	+2400	No. 34	−3.6	−3.7	+1455
No. 9	−4.2	−4.5	−920	No. 35		Missing	
No. 10	−4.6	−4.6	−625	No. 36	−6.5	−5.2	−480
No. 11	−1.6	−1.3	−175	No. 37	−4.5	−4.2	−1435
No. 12		Standard		No. 38	−5.4	−5.1	−2210
No. 13	+2.2	+2.5	+1560	No. 39	−4.7	−4.4	−1760
No. 14	+5.7	+6.0	+2960	No. 40	−5.8	−5.7	−3380
No. 15		Broken		No. 41	−3.7	−3.3	−1040
No. 16	−7.7	−6.7	−1470	No. 42	−1.9	−2.3	−1620
No. 17	−3.8	−2.8	−1260	No. 43	+15.2	+12.1	+5625
No. 18	+2.3	+3.0	+1520	No. 44	+2.7	+4.0	+330
No. 19	−9.7	−8.2	−3970	No. 45	+14.3	+18.4	+5050
No. 20	−9.2	−8.0	−3670	No. 46	−2.3	−1.2	+195
No. 21	−5.9	−4.2	−2470	No. 47	+1.8	+2.9	+1750
No. 22	−0.8	+0.4	−330	No. 48	−2.8	−2.7	−620
No. 23	+15.5	+18.0	+3410	No. 49	0.0	+0.6	+1170
No. 24	+11.2	+13.8	+2760	No. 50	+6.3	+6.7	+3020
No. 25	−3.5	−3.0	−1280	No. 51	−3.8	−3.4	−1170
No. 26	−7.9	−5.9	−1650	No. 52	−1.0	+1.9	+1420

Wattmeter Test.—Mr. Spooner was able to check his loss measurements at 10 cycles with a wattmeter measurement. In this test the primaries of the two coils were in series with the current coils of a dynamometer wattmeter, and the secondaries connected in opposition to the moving coil of the instrument. Drill No. 12, the standard, was placed in one coil and readings were taken with the other drills placed successively in the other coil.

Operation.—In the alternating current tests the magnetizing force H equalled approximately 148 gausses with an exciting current of 3.75 amperes. Two inches of the length of the drill $\frac{1}{4}$ in. from the cutting end formed the core of the transformer. The hole in the bakelite tube upon which the windings were wound was $\frac{5}{8}$ in. in diameter and it was found possible to move the drills about in this space, as long as no attempt was made to withdraw them, without changing the reading of the galvanometer. The placing of the drills in the transformer was a simple matter, and the readings could be taken quickly and without difficulty. The 50 drills could be tested within 30 minutes with the equipment used. Great care was necessary in adjusting the phase of the field excitation of the galvanometer, as a slight error in adjustment would change the results, especially the "H.C. Read" and "A.C. Loss" values. A constant voltage was applied to the field of the galvanometer in all the tests.

TABLE III.—RESULTS OF THE "H_c A.C. READ" TESTS.

Drill	Spooner's Method, 10 cycles	Kouwenhoven's Method	
		10 cycles	60 cycles
No. 1	−2.7	−1.5	−1.3
No. 2	+6.7	+0.9	+1.0
No. 3	+5.7	−0.1	+1.0
No. 4	+10.0	−3.6	+5.0
No. 5	−7.4	−1.1	−3.3
No. 6	−2.3	−0.1	−1.8
No. 7	−3.6	−1.7	−1.6
No. 8	+9.2	−1.8	−3.7
No. 9	−7.4	−0.4	−3.3
No. 10	−8.2	−0.7	−3.5
No. 11	−1.9	−0.5	−1.0
No. 12	Standard		
No. 13	+2.2	−2.0	+1.7
No. 14	+7.4	−2.5	+3.8
No. 15	Broken		
No. 16	−15.0	−2.3	−5.0
No. 17	−7.3	−2.3	−2.2
No. 18	+1.5	−3.1	+2.1
No. 19	−18.0	−2.3	−6.1
No. 20	−18.0	−2.3	−6.0
No. 21	−11.0	−2.6	−3.5
No. 22	−2.5	−2.6	0.0
No. 23	+6.2	−14.9	+12.3
No. 24	+4.6	−12.0	+9.3
No. 25	−5.4	−0.5	−1.8
No. 26	−16.8	−3.6	−4.7
No. 27	−0.8	+0.4	−0.8
No. 28	+3.3	+0.8	+0.2
No. 29	+7.7	−2.5	+4.2
No. 30	−3.0	+0.3	−1.4
No. 31	−5.5	−1.0	−2.2
No. 32	−3.0	−0.7	−1.3
No. 33	+0.7	−2.2	+1.3
No. 34	−6.0	−0.2	−2.4
No. 35	Missing		
No. 36	−15.0	−3.5	−4.0
No. 37	−9.7	−1.8	−3.0
No. 38	−7.6	+0.3	−3.6
No. 39	−8.1	−0.6	−3.2
No. 40	−5.7	+2.0	−4.1
No. 41	−6.3	−0.6	−2.3
No. 42	−1.3	+1.2	−1.4
No. 43	+7.6	−9.0	+7.4
No. 44	−1.3	−5.7	−2.4
No. 45	+5.6	−16.3	+9.9
No. 46	−3.0	−1.2	−1.4
No. 47	+3.2	−1.9	+1.5
No. 48	−3.9	−0.2	−2.0
No. 49	−1.1	−2.2	0.0
No. 50	+7.8	−3.1	+4.6
No. 51	−5.5	−0.3	−2.5
No. 52	+1.9	−1.7	+0.9

Results.—The results of the A.C. tests are given in Tables II, III, and IV. The alternating magnetic flux does not penetrate uniformly to the center of the drill on account of the phenomenon known as skin effect, and therefore the A.C. readings apply only to a relatively thin layer of metal near the surface. The thickness of this layer can only be roughly estimated when we know how the permeability of the metal varies under the conditions of the test.

In Table II, columns 2 and 3, and 6 and 7 give the A.C. "B_m" readings at 60 and 10 cycles. The readings are given in terms of galvanometer deflections in centimeters, the minus sign indicating a drill that has a lower B_m and the plus sign a drill that has a higher B_m than the standard drill No. 12. In columns 4 and 8 of this table are to be found the differences between the B_m of drill No. 12 and that of the other drills as calculated from D. C. permeameter readings.

TABLE IV.—"A.C. LOSS" RESULTS.

Drill	Spooner's Method, 10 cycles	Kouwenhoven's Method		Drill	Spooner's Method, 10 cycles	Kouwenhoven's Method	
		10 cycles	60 cycles			10 cycles	60 cycles
No. 1.......	0.0	−7.2	+6.5	No. 27.......	+0.8	−2.4	+1.4
No. 2.......	+8.5	+4.1	+11.9	No. 28.......	+4.8	+1.2	+2.9
No. 3.......	+8.0	+1.4	+11.6	No. 29.......	+10.6	−2.4	+7.3
No. 4.......	+13.8	−2.0	+18.0	No. 30.......	−0.9	−3.1	+0.3
No. 5.......	−4.5	−8.8	−0.5	No. 31.......	−2.7	−7.5	−1.5
No. 6.......	0.0	−3.5	−1.0	No. 32.......	−0.7	−5.9	−0.7
No. 7.......	−0.8	−7.8	+1.1	No. 33.......	+3.7	−6.9	+1.7
No. 8.......	+12.3	+1.7	+9.6	No. 34.......	−3.2	−5.9	−2.0
No. 9.......	−4.5	−6.6	−3.5	No. 35.......		Missing	
No. 10.......	−5.2	−8.0	−1.3	No. 36.......	−10.3	−18.4	−7.1
No. 11.......	+0.3	−3.8	+1.1	No. 37.......	−5.9	−11.1	+0.5
No. 12.......		Standard		No. 38.......	−4.9	−5.3	−2.6
No. 13.......	+4.9	−4.6	+4.1	No. 39.......	−4.9	−7.7	−3.5
No. 14.......	+10.8	−1.2	+7.5	No. 40.......	−3.9	−1.1	−2.0
No. 15.......		Broken		No. 41.......	−3.3	−6.8	−2.1
No. 16.......	−11.0	−15.9	−5.6	No. 42.......	+0.7	+0.2	+0.4
No. 17.......	−4.5	−12.0	+2.5	No. 43.......	+14.2	−11.4	+12.6
No. 18.......	+4.5	−8.2	+4.0	No. 44.......	+1.6	−16.2	+5.2
No. 19.......	−13.7	−17.6	−7.3	No. 45.......	+17.3	−22.0	+24.0
No. 20.......	−13.1	−17.0	−7.3	No. 46.......	−1.0	−7.7	−1.2
No. 21.......	−8.0	−15.5	+0.5	No. 47.......	+5.4	−4.4	+2.3
No. 22.......	−0.1	−11.0	+1.0	No. 48.......	−1.7	−4.9	−1.8
No. 23.......	+17.5	−23.5	+23.5	No. 49.......	+1.3	−7.5	+0.1
No. 24.......	+12.6	−20.5	+20.4	No. 50.......	+11.1	−2.5	+5.6
No. 25.......	−2.9	−6.5	−1.1	No. 51.......	−3.2	−6.5	−2.4
No. 26.......	−11.5	−19.0	−6.8	No. 52.......	+4.0	−4.5	+2.0

HARDNESS TESTS

The hardness tests on the A.S.T.M. drills were made by J. V. Emmons of the Cleveland Twist Drill Co. His report is given below:

REPORT OF HARDNESS TESTS ON A.S.T.M. DRILLS

The first test made on the drills was the Rockwell hardness test. An aluminum body demonstrating Rockwell machine was used. The hardness readings of all the drills, with the exception of Nos. 23, 24 and 45, were taken under 150-kg. pressure, using a diamond cone. Nos. 23, 24 and 45 were taken under 100-kg. pressure with a $\frac{1}{16}$-in. steel ball, because their extreme softness would not permit the use of the diamond cone and heavier pressure. In order to carry out the tests a special V block was made as long as the flutes of the drills. This was done to give the drills the best support possible and to hold them absolutely horizontal. Readings were taken on the lands and on the flutes. The average of the readings was taken as the correct Rockwell hardness number.

The next step consisted of cutting a $\frac{1}{2}$-in. piece off the end of each drill with a thin alundum disk. Great care was taken in this operation and in all the grinding and polishing operations not to heat the drills or sections. This $\frac{1}{2}$-in. piece was used later for the Brinell test and microscopic examination.

The ends of the drills were ground off square and the scleroscope readings taken. The drills were tightly held in a vise having copper jaws. The ends of the drills were flush with the top of the jaws. The margins of the drills were used as the points of contact with the jaws, and the readings taken in a straight line between the points of contact. In this way, all the drills were tested in as nearly the same manner as possible. Five readings were taken and the average of these readings used as the correct scleroscope hardness. The drills were tested by three different men and the average of their determinations reported as the hardness.

The Brinell hardnesses were next determined. In order to prepare the ½-in. sections for Brinelling, the pointed sides were ground off on a Blanchard Magnetic Grinder. This made the sections of exactly the same thickness and the sides parallel. One side of the sections was polished with 2*F* alundum flour to give a good surface for Brinelling. The Brinell hardnesses of the sections were determined by two men and cross-checked to eliminate any errors in reading the diameters of the impressions. The averages of the readings by the two men were taken as the correct hardness. The tests were made with a hydraulic testing machine made by the Pittsburgh Instrument and Machine Co.

TABLE V.—HARDNESS DETERMINATIONS UPON THE A.S.T.M. DRILLS.

Drill	Hardness			Drill	Hardness		
	Rockwell	Sclereoscope	Brinell		Rockwell	Sclereoscope	Brinell
No. 1	C-52	74	562	No. 27	C-60	83	611
No. 2	C-48	73	549	No. 28	C-57	83	639
No. 3	C-49	74	545	No. 29	C-56	81	616
No. 4	C-44	69	492.5	No. 30	C-58	83	654
No. 5	C-59	85	659	No. 31	C-57	86	654
No. 6	C-57	81	622	No. 32	C-61	85	670.5
No. 7	C-57	81	616	No. 33	C-63	87	704
No. 8	C-54	81	616	No. 34	C-57	85	654
No. 9	C-62	85	687.5	No. 35	....	....	....
No. 10	C-58	84	654	No. 36	C-62	83	659
No. 11	C-60	84	659	No. 37	C-61	84	659
No. 12	C-61	84	659	No. 38	C-58	85	654
No. 13	C-59	86	682	No. 39	C-56	83	654
No. 14	C 56	83	649	No. 40	C-54	84	670.5
No. 15	....	....	....	No. 41	C-62	84	659
No. 16	C-59	84	659	No. 42	C-55	84	659
No. 17	C-56	86	659	No. 43	C-62	87	639
No. 18	C-59	87	659	No. 44	C-59	83	611
No. 19	C-47	80	616	No. 45	B-86	35	167.5
No. 20	C-48	83	597	No. 46	C-54	78	616
No. 21	C-52	86	604.5	No. 47	C-55	79	611
No. 22	C-40	85	639	No. 48	C-60	84	659
No. 23	B-95	37	205.5	No. 49	C-60	86	659
No. 24	B-92	40	208.5	No. 50	C-53	79	611
No. 25	C-55	85	654	No. 51	C-58	85	644
No. 26	C-35	84	665	No. 52	C-63	87	665

Five-millimeter Hoover micro-chrome steel balls were used. The balls were carefully inspected after each test on the hard drills and all deformed balls rejected.

A pressure of 1000 kg. was used on all the drill sections, with the exception of Nos. 23, 24 and 45, and on them only 500-kg. pressure was used.

Drilling Test

The drilling or cutting tests were also conducted by J. V. Emmons of the Cleveland Twist Drill Co., and his report follows:

Report on Drilling Tests of the A.S.T.M. Drills

These tests consisted of drilling in four different materials of widely differing properties.

The total penetration in inches by each drill in each material was recorded.

Table VI.—Arrangemnt of Drills in Order of Their Drilling Performance

Ranking	Drill	Quality	Ranking	Drill	Quality
1	No. 32	High Quality	26	No. 36	Medium Quality
2	No. 31	High Quality	26	No. 38	Medium Quality
3	No. 26	High Quality	28	No. 2	Low Quality
4	No. 13	High Quality	29	No. 18	Low Quality
5	No. 33	High Quality	30	No. 47	Low Quality
6	No. 14	High Quality	31	No. 5	Low Quality
6	No. 49	High Quality	31	No. 9	Low Quality
8	No. 30	High Quality	33	No. 7	Low Quality
9	No. 10	Medium Quality	34	No. 3	Low Quality
10	No. 41	Medium Quality	35	No. 50	Low Quality
11	No. 48	Medium Quality	36	No. 8	Low Quality
12	No. 12	Medium Quality	36	No. 46	Low Quality
13	No. 17	Medium Quality	38	No. 1	Low Quality
14	No. 34	Medium Quality	39	No. 4	No commercial value
15	No. 25	Medium Quality	40	No. 40	No commercial value
15	No. 42	Medium Quality	41	No. 16	No commercial value
17	No. 11	Medium Quality	41	No. 19	No commercial value
17	No. 27	Medium Quality	41	No. 20	No commercial value
17	No. 51	Medium Quality	41	No. 21	No commercial value
20	No. 39	Medium Quality	41	No. 22	No commercial value
21	No. 36	Medium Quality	41	No. 23	No commercial value
22	No. 37	Medium Quality	41	No. 24	No commercial value
23	No. 29	Medium Quality	41	No. 43	No commercial value
23	No. 52	Medium Quality	41	No. 44	No commercial value
25	No. 28	Medium Quality	41	No. 45	No commercial value

Each test was carried until the drill refused to penetrate further. In some cases, however, the drill broke before the point had ceased to penetrate.

All of the tests were performed upon one drill press and by one operator, in order to eliminate variables due to lack of uniformity of operation.

The points were all machine ground on a Worcester point grinder and carefully inspected for uniformity at the beginning of each test. The points were thinned at the center when necessary.

The speeds and feeds of the drill press were carefully checked during the progress of the test.

The conditions of the first test in chrome die steel were planned to give a good wearing test to the point without endangering the weaker drills.

The conditions in the second test in heat-treated armor plate were planned to determine the ability of the drills to penetrate hard material of high tensile strength. No soft drill would show up favorably in this test.

The third test in soft tough steel with a heavy feed was designed to eliminate the drills that were either too weak or too brittle.

The fourth test being made in cast iron without lubricant under very severe conditions required of the drills a high degree of red hardness. The wearing qualities and torsional strength of the drills were also pushed to the limit by this test.

After each test, the drills were ranked in the order of their performance. The total of these rankings in the four tests was then used to obtain the "Summary of the Rank Earned."

A second method of comparing the performance of the drills was by rating them according to the total number of inches drilled in the four tests.

The final rating was obtained by combining the results of these two methods giving an equal value to each.

For convenience in study, the drills are arranged, as given in Table VI, in the order of their drilling performances and roughly classified into four groups, namely, high quality, medium quality, low quality, no commercial value.

Mr. Emmons classified 8 of the drills as being of high quality and 19 others of medium quality, making a total of 27 good drills in the 52 samples furnished for the test. Of the remainder, eleven are classed as low quality drills and the balance have no commercial value.

CLASSIFICATION OF THE DRILLS BY MAGNETIC TESTS

An attempt was made to classify the drills by means of the magnetic data, and to choose the proper magnetic test limits which would eliminate the bad drills from the set and pass the 27 good drills.

The D. C. tests were first studied and it was found that no single D. C. test would serve the purpose. If we apply the D. C. B_m test to all of the drills and accept only those drills whose B_m readings lie between the limits of 7900 and 12,000 we will have drills Nos. 1, 2, 3, 5, 6, 7, 10, 11, 12, 13, 17, 18, 22, 25, 26, 27, 28, 30, 31, 32, 33, 34, 36, 37, 39, 41, 42, 44, 46, 47, 48, 49, 51 and 52.

If we now apply the coercive force test to the 34 drills that passed the B_m test, and choose as limits $+1.6\ B_c$ to $-0.7\ B_c$, we have left drills Nos. 5, 6, 7, 10, 11, 12, 13, 17, 25, 26, 27, 28, 30, 31, 32, 34, 36, 37, 39, 41, 42, 48 and 51.

Of these 23 drills that have passed the D. C. magnetic tests, 21 are good quality drills and two, namely, Nos. 5 and 7, are low quality drills. If the limits are made close enough to eliminate these two low quality drills only four drills would pass the test. Furthermore, the residual magnetism "B_r" values do not aid us in eliminating these two low quality drills.

The alternating current magnetic test results were next tried and it was found that the B_m readings for the drills at both 10 and 60 cycles were of little assistance in eliminating poor drills.

If we apply the 60-cycle "H_c A.C. Read" test to the drills and accept only those drills whose values lie between +1.4 and −3.2 we have drills Nos. 1, 2, 3, 6, 7, 11, 12, 17, 22, 25, 27, 28, 30, 31, 32, 33, 34, 37, 39, 41, 42, 44, 46, 48, 49, 51 and 52 as satisfactory. As a second test we will apply the "A.C. Loss" 60-cycle test and accept only those drills which fall between the limits of +0.9 and −4.0. We then have as good drills Nos. 6, 11, 25, 30, 31, 32, 34, 37, 39, 41, 42, 46, 48, 49 and 51. Of these 15 drills which are passed by these two 60-cycle tests, 14 are good quality drills and one drill, No. 46, is a low quality drill.

A slightly higher positive limit will pass more good drills but will also include drills of low quality or of no commercial value.

If we apply the 10-cycle "H_c A.C. Read" (Kouwenhoven's) to the 52 drills and set our acceptance limits at +1.2 and −2.5, we pass the following drills, namely, Nos. 1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 19, 20, 25, 27, 28, 29, 30, 31, 32, 33, 34, 37, 38, 39, 41, 42, 46, 47, 48, 49, 51 and 52.

As a second test we will apply the "A.C. Loss" (Kouwenhoven's) at 10 cycles to these drills that have passed the 10-cycle "H_c A.C. Read" test. As limits we will use +1.2 and −7.6. Then we will pass the following drills, Nos. 1, 6, 9, 11, 12, 13, 14, 25, 27, 28, 29, 30, 31, 32, 33, 34, 38, 41, 42, 47, 48, 49, 51 and 52. Of these 24 drills that have passed the tests, 21 are of good quality and three, namely, Nos. 1, 9 and 47, are of low quality.

If we should apply a third test to the 24 drills that passed the two 10-cycle tests we can eliminate one of these low quality drills. As an example, suppose we use Mr. Spooner's "A.C. Loss" setting at 10 cycles and take as our limits +5.3 to −5.0. Then we will accept drills Nos. 1, 6, 9, 11, 12, 13, 25, 27, 28, 30, 31, 32, 33, 34, 38, 41, 42, 48, 49, 51 and 52. Now if we shift our frequency to 60-cycles and apply the "A.C. Loss" test at that frequency, choosing as our limits +6.4 and −3.4, then we will pass drills Nos. 6, 11, 12, 13, 25, 27, 28, 30, 31, 32, 33, 34, 38, 41, 42, 48, 49, 51 and 52. These 19 drills are all of good quality.

Another method that gives good results is to apply tests at two frequencies. If we put the drills through the "A.C. Loss" test at 10-cycles and choose as our limits +1.2 to −7.6 we will pass drills Nos. 1, 4, 6, 9, 11, 12, 13, 14, 25, 27, 28, 29, 30, 31, 32, 33, 34, 38, 40, 41, 42, 47, 48, 49, 50, 51 and 52. As a second test, use 60 cycles and pass those drills whose values lie between +2.2 and −3.4 limits of the "A.C. Loss" test. Then we have drills Nos. 6, 11, 12, 25, 27, 30, 31, 32, 33, 34, 38, 40, 41, 42, 48, 49, 51 and 52. These 18 drills are all of good quality except drill No. 40 which is of no commercial value. Drill No. 40 may be easily eliminated by the "H_c A.C. Read" test at 60 cycles using the limits of +5.0 to −4.0. This test will pass all of the remaining 17 good quality drills.

It is possible to eliminate not only all of the low quality and no commercial value drills but also all except three of the medium quality drills from the 52 samples by applying five magnetic tests with properly chosen limits. The drills passing these tests are Nos. 6, 11, 13, 27, 30, 31, 32, 33 and 49. Six of these drills are listed by Mr. Emmons as being of the best quality; the others, namely, Nos. 6, 11 and 27, are of the better class medium quality.

There are a number of orders in which the tests may be applied and a wide choice of limits that may be used. The writer, however, feels that the above will serve as an example of what can be done with the data at hand.

CLASSIFICATION OF DRILLS BY HARDNESS TESTS

If we accept as good, all drills that have a Rockwell hardness reading from C 63 to C 55, inclusive, we will pass 7 first quality drills, 17 medium quality, 7 low quality and 3 drills of no commercial value. This gives a total of 24 good drills.

If we apply the Brinell test and accept all drills whose hardness numbers lie between 666 and 638, we will pass 6 first quality drills, 16 medium quality, 2 low quality and 3 drills of no commercial value. These limits pass a total of 22 good drills.

Summation of Magnetic and Hardness Classification.—The table below gives a summation of the results obtained in the magnetic and hardness classification tests listed above:

	Magnetic Tests					Hardness Tests	
	D.C., 2 tests	60 cycle A.C., 2 tests	10 cycle A.C., 2 tests	10 and 60-cycle A.C., 4 tests	10 and 60-cycle A.C., 3 tests	Rockwell	Brinell
Number of First Quality Drills	4	4	7	6	5	7	6
Number of Medium Quality Drills	17	10	14	13	12	17	16
Number of Good Quality Drills[a]	21	14	21	19	17	24	22
Number of Low Quality Drills	2	1	3	0	0	7	2
Number of No Value Drills	0	0	0	0	0	3	3
Total Number Passed	23	15	24	19	17	34	27

[a] Good quality drills include all first and medium quality drills.

CONCLUSIONS

A comparison of the results of the drilling tests with those of the magnetic and hardness tests shows that certain drills that did well in the actual drilling test have widely different magnetic and hardness properties. The reason for this is not known.

In the magnetic A.C. tests, drill No. 12 was taken as the standard because the author assumed that it had received the correct heat treatment. The drilling tests showed that No. 12 was only a medium quality drill. This, however, should make no difference in the A.C. tests.

If a single group of first quality drills, for example, Nos. 30, 31, 32, 33 and 49, are selected and the proper limits chosen it is a comparatively simple matter to eliminate the other drills by means of the magnetic tests. The elimination tests listed above show what can be done by the use of the magnetic tests in eliminating the drills of low quality and of no commercial value. The results show that the magnetic tests are more successful in picking out the good drills than are the hardness tests. The results also show clearly the value of the A.C. method. Further investigation is in progress.

CHAIN: EFFECT OF PROOFING AND ANNEALING ON BRITTLENESS IN LARGE CHAIN LINKS

By C. G. Lutts[1]

It has for some time been recognized at the Boston Navy Yard that wrought-iron chain of the larger sizes frequently exhibits properties of extreme brittleness. Instances are known where ships' chain cables have been fractured through falling or striking on an unyielding surface. A test is on record where one very large-size chain link, $3\frac{3}{8}$ in. wire diameter, broke through its end when dropped once from a height of 16 ft. Large chain cable links which have failed in service usually show this brittleness (Fig. 1).

It was established some time ago that this brittleness could be induced in chain by overstraining. The investigation described in this paper was accordingly undertaken with a view of determining the factors and their influence on brittleness in links. Attention has been given to the effect of proof loading. Study has also been made as to the effect of annealing, a practice commonly accepted and performed, but concerning which few definite data have been published.

Scope of the Investigation

This paper deals principally with large chain such as is used for anchor chain. However, one group of tests on small chain, $1\frac{3}{8}$ in. in size, has been included. The study as to the effect of proofing has been confined to one value of proof load, namely, 60 per cent of the required breaking load of the links. This proof load is the one ordinarily used for new stud chain. The effect of larger or smaller loads is not reported upon. The studies as to the efficacy of annealing have been limited to a consideration of three temperatures: 960, 700, and 600° C.

Material

All links used for these tests were of wrought iron, and, with the exception of four, were end-lap-welded. These four were side-lap-welded. The links of the first three test groups were of doubly-

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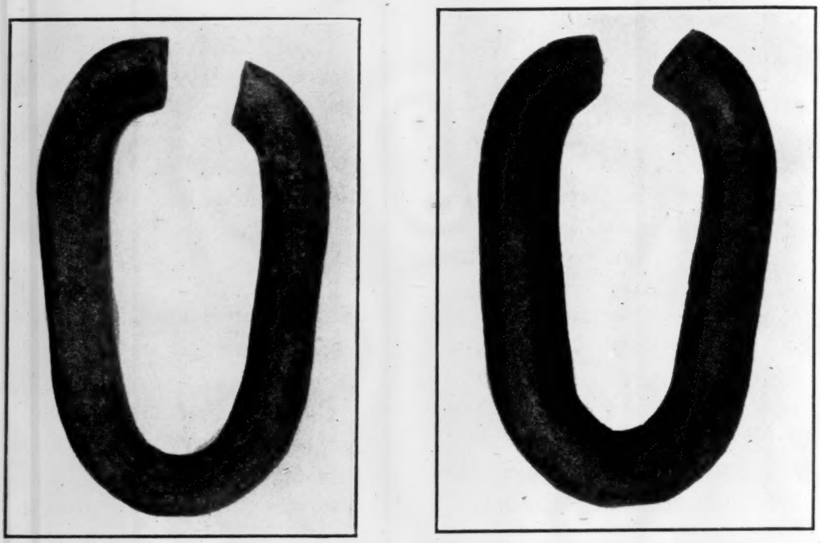
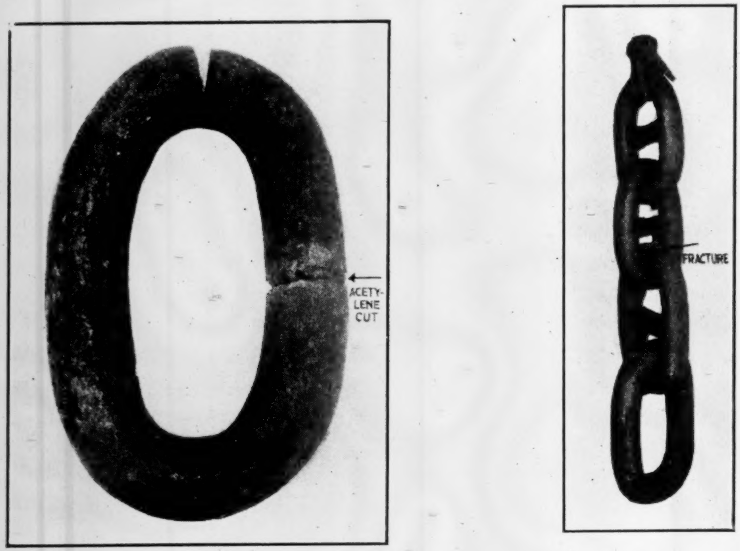
[1] Metallurgist, U. S. Navy Yard, Boston, Mass.



(*a*) 3-in. "G" Link. Fracture at Welded End. No Excessive Strain.

(*b*) $3\frac{3}{4}$-in. "G" Link. Fracture at Welded End. Chain Parted During Heavy Swell.



(*c*) 3-in. "F" Link. Fracture at Welded End. No Excessive Strain at Time of Fracture.

(*d*) $3\frac{1}{4}$-in. "F" Link. Fracture at Welded End.

FIG. 1.—Large Wrought-Iron Chain Links which Failed in Service, Showing Sharp and Short Fractures.

refined wrought iron meeting Navy specifications for this grade. The links of the fourth and last test group were of good quality commercial chain iron.

First Group (Links of Table I).—These links were of $2\frac{3}{4}$ in. wire diameter stud links manufactured by the power welding process at the Boston Navy Yard. They were originally used for a study of the effect of repeated proof loading on chain, and previous to shock testing had been subjected to 150,000 applications of the proof load of 267,000 lb.

TABLE I.—TESTS OF $2\frac{3}{4}$-IN. WROUGHT-IRON STUD LINKS.

Previously Proof Loaded 150,000 Times

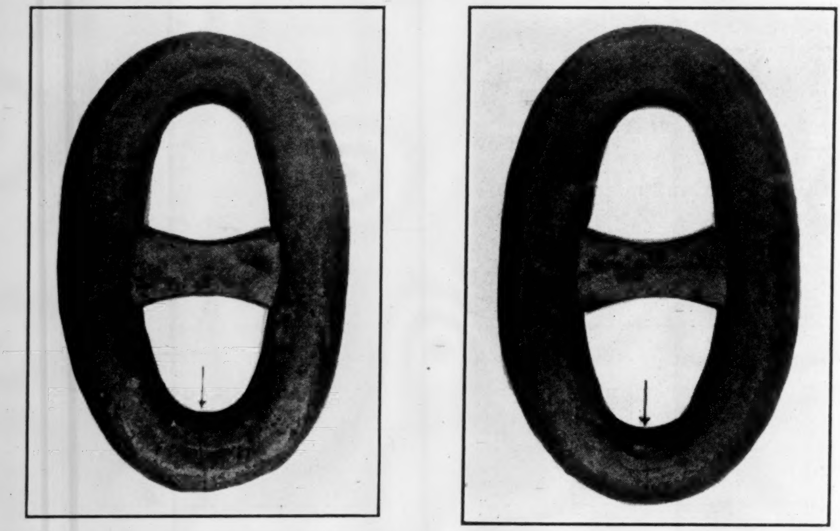
As Received					Annealed at 960° C.					Annealed at 960° C. Proofed at 266,800 lb.				
Link No.	End Hit	Fracture		No. of Drops	Link No.	End Hit	Fracture		No. of Drops	Link No.	End Hit	Fracture		No. of Drops
		Location	Type				Location	Type				Location	Type	
HAMMER TEST														
9	W	W	S&S	35	22	W	NB	NB	200	53	SW	NB	NB	180
17	B	B	S&S	4	27	B	NB	NB	200					
18	W	W	S&S	11	33	W	NB	NB	200					
19	W	W	S&S	32	54	SW	NB	NB	200					
20	B	B	S&S	6										
24	W	B	S&S	15										
30	W	W	S&S	5										
Average				15.4					200					180
16-FT. DROP TEST														
5[a]	W	W	S&S	2	16	W	W	WW	19	12	B	NB	NB	100
8	W	W	S&S	20	26	B	NB	NB	100	28	B	W	WW	25
10	W	W	S&S	16	32	W	NB	NB	100	34	W	B	S&S	15
14	B	B	S&S	7	4[a]	W	NB	NB	100	52	SW	NB	NB	100
23	W	W	S&S	25						55		NB	NB	100
25	B	NB	NB	100										
Average				28.3					79.7					68

W=Welded end. B=Bent end. S&S=Sharp and short. WW=With weld. NB=No break. SW=Side Welded.

[a] Nos. 4 and 5 dropped as a doublet. No. 4 was dropped below No. 5 and struck, but No. 5 broke at end connected with No. 4.

Second Group (Links of Table II).—These links were of $2\frac{5}{8}$-in. wire diameter stud links, power welded, and were cut from chains made in 1920 which had not been used. At the time of manufacture these chains were annealed at 960° C. for ten minutes and subsequently proofed to 244,000 lb. Eight different chains were represented in this group of links.

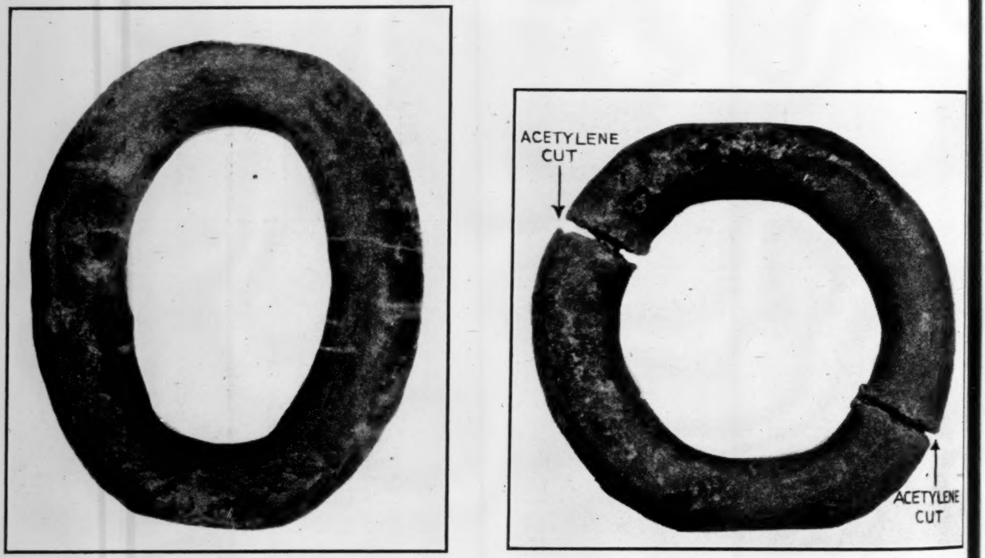
Third Group (Links of Table III).—These were of $2\frac{3}{4}$-in. wire diameter links, hand welded in 1916. The chains represented by hese links were new in that they had not been used, but they had,



(*a*) Link No. 19. Hit on Welded End. Broke Sharp and Short at Welded End at 32 Blows.

(*b*) Link No. 20. Hit on Bent End. Broke Sharp and Short at Bent End at 6 Blows.

NOT ANNEALED

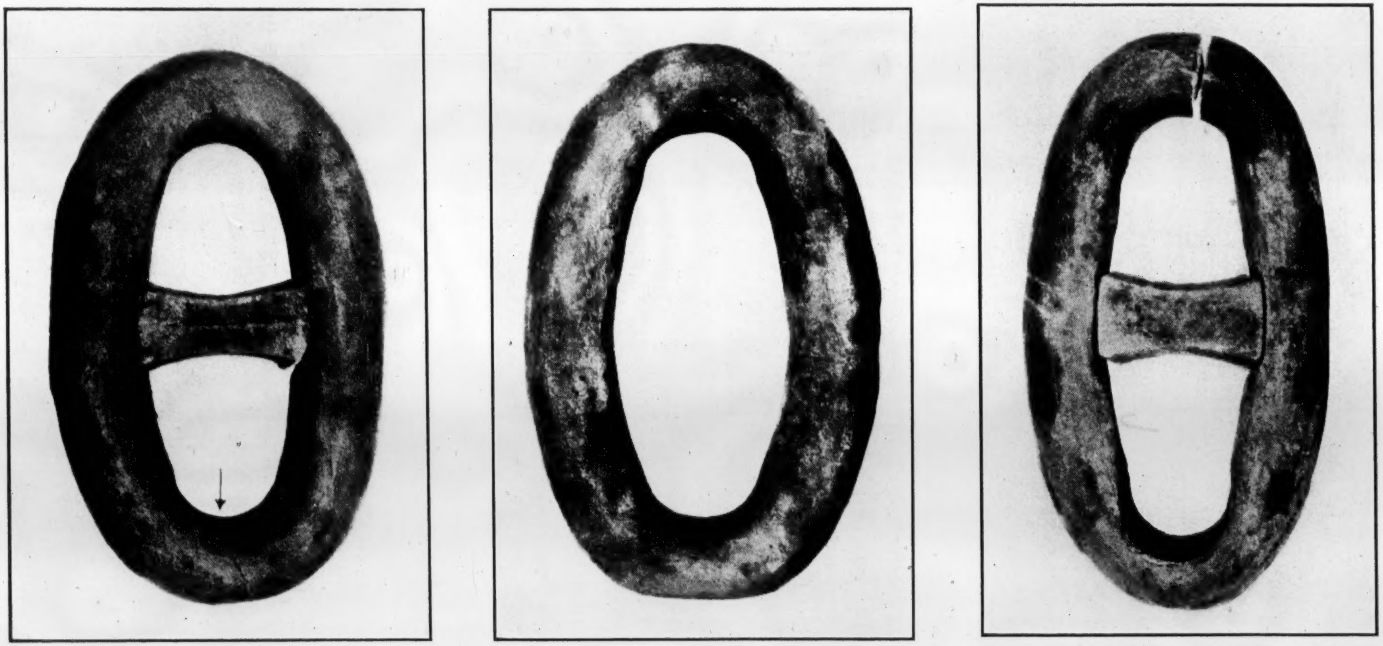


(*c*) Link No. 22. Hit on Welded End. Did not Break at 200 Blows.

(*d*) Link No. 27. Hit on Bent End. Did not Break at 200 Blows. Note Change of Shape.

ANNEALED AT 960° C.

FIG. 2.—Wrought-Iron Chain Links Subjected to Hammer Test (see Table I), Previously Proof Loaded 150,000 Times.



(*a*) Link No. 23. Unannealed. Dropped on Welded End. Broke Sharp and Short at Welded End at 25 Drops.

(*b*) Link No. 26. Annealed at 960° C. Dropped on Welded End. Did not Break at 100 Drops.

(*c*) Link No. 34. Annealed at 960° C., Proofed at 266,800 lb. Dropped on Welded End. Broke Sharp and Short at Bent End at 15 Drops.

FIG. 3.—Wrought-Iron Chain Links Subjected to 16-ft. Drop Test (see Table I), Previously Proof Loaded 150,000 Times.

however, been exposed to the weather for a number of months. At the time of manufacture these chains were annealed at 960° C. and subsequently proofed to 222,000 lb. Thirty-six different chains or shots were represented by these links.

Fourth Group (Links of Table IV).—These were of $1\frac{3}{8}$-in. links, hand welded in 1915. The chain had been in service over a considerable period of time. Only one chain was represented by these links.

METHODS OF TEST

Two methods for shock testing were employed, a hammer test and a drop test.

Hammer Test.—A board drop hammer was used for this test. Individual links were held on end on the hammer anvil and were struck by the 1080-lb. ram, falling freely from increasing heights of 6, 8, 12, 14 and 20 in. The blows were applied as follows: one at 6 in., one at 8 in., one at 12 in., 150 at 14 in., and 50 at 20 in. This method of test was used for twelve links; these are reported upon in the first portion of Table I. It was felt, however, that this method was open to the objection that the combination of a heavy weight with small drop did not simulate service conditions. This first method was, therefore, discontinued in favor of a second method.

Drop Test.—This method consisted in dropping individual links from a height of 16 ft., their ends striking on a solid steel block weighing about 2000 lb. In practice, a free and accurate drop was accomplished through cutting the string by which the link was suspended at the hoisting hook. The majority of the links were dropped welded end down; a few were dropped bent end down.

RESULTS OF TESTS

Tables I, II, III and IV give the results of the tests. Photographs shown in Figs. 2 and 3 are typical of links noted in Table I. Fig. 2 shows certain links tested by the board drop hammer method; Fig. 3 shows links tested by the 16-ft. drop method.

Explanation of Tables.—The designation "shot number" in Tables II and III has reference to chains represented by the links tested. The column "location of fracture" refers to *W*, meaning welded end of link, or *B*, meaning bent end of link. The appearance of the fracture is described either by the designation *S&S* meaning sharp and short, or *WW* meaning with the weld. For those instances classified *S&S*, the fracture extended entirely through the wire of the link. When classified *WW*, the fracture was well developed, but usually did not extend the entire length of the weld; that is, a failure was recorded when the weld in part opened definitely.

TABLE II.—16-FT. DROP TESTS OF $2\frac{5}{8}$-IN. STUD LINKS FROM EIGHT SHOTS OF NEW CHAIN.

LINKS DROPPED ON WELDED END

Shot No.	As Received			Annealed at 960° C.			Annealed at 960° C. Proofed at 244,000 lb.			Annealed at 700° C.			Annealed at 600° C.		
	Fracture		No. of Drops	Fracture		No. of Drops	Fracture		No. of Drops	Fracture		No. of Drops	Fracture		No. of Drops
	Location	Type		Location	Type		Location	Type		Location	Type		Location	Type	
998	W	S&S	39	W	WW	52	W	S&S	30	W	WW	184	W	S&S	59
1145	W	S&S	3	NB	NB	200	W	S&S	64	W	S&S	189	NB	NB	200
1147	W	S&S	34	NB	NB	200	W	S&S	86	W	S&S	164	W	S&S	103
1173	NB	NB	100	W	WW	151	W	S&S	19	W	WW	198	W	S&S	161
1174	W	S&S	97	W	S&S	180	W	S&S	11	W	S&S	45	W	S&S	172
1289	[a]	S&S	93	W	S&S	101	W	S&S	17	W	WW	198	W	WW	165
1294	W	S&S	57	W	S&S	156	W	S&S	79	W	S&S	93	W	WW	101
1383	NB	NB	100	W	S&S	142	W	S&S	88	NB	NB	200	B	S&S	170
Average.........			65			148			49			159			141

W = Welded end. B = Bent end. S&S = Sharp and short. WW = With weld. NB = No break.

[a] Welded end and Bent Quarter.

TABLE III.—16-FT. DROP TEST OF $2\frac{3}{4}$-IN. WROUGHT-IRON LINKS FROM VARIOUS SHOTS OF NEW CHAIN.

LINKS DROPPED ON WELDED END

As Received					Annealed at 960° C.					Annealed at 960° C. Proofed at 222,500 lb.					Annealed at 700° C.					Annealed at 600° C.				
Shot No.	Type of Link	Fracture		No. of Drops	Shot No.	Type of Link	Fracture		No. of Drops	Shot No.	Type of Link	Fracture		No. of Drops	Shot No.	Type of Link	Fracture		No. of Drops	Shot No.	Type of Link	Fracture		No. of Drops
		Location	Type				Location	Type				Location	Type				Location	Type				Location	Type	
1060	E	W	S&S	4	987	E	W	WW	31	1012	E	B	S&S	3	995	C	NB	NB	100	1000	C	W	WW	33
1057	E	W	WW	3	1055	E	W	WW	25	1012	C	W	WW	10	999	C	W	WW	50	999	E	W	WW	13
988	E	W	WW	7	1063	E	W	WW	60	1055	C	W	S&S	8	1010	E	W	S&S	4	1057	C	W	WW	17
1059	C	W	S&S	3	1009	E	W	WW	59	1008	C	W	S&S	21	997	E	W	S&S	18	996	E	W	WW	18
1207	E	W	S&S	7	986	E	W	WW	15	990	C	W	S&S	21	988	C	W	WW	56	1013	E	W	WW	16
1002	C	W	S&S	3	998	E	W	WW	19	1027	E	W	S&S	6	423	E	W	WW	33	1307	E	W	S&S	55
1020	C	W	S&S	1	1001	E	W	WW	31	990	E	W	S&S	8	50	E	W	S&S	31	395	E	W	S&S	22
44	C	B	S&S	22	1007	E	W	WW	30	1056	E	W	WW	24										
996	C	W	S&S	8	1027	C	W	WW	33	1026	C	W	S&S	3										
123	C	W	S&S	3																				
1010	C	W	S&S	1																				
1013	C	W	S&S	2																				
Average....				5.3					33.6					11.5					41.7					24.8

DROPPED ON BENT END

As Received					Annealed at 960° C.					Annealed at 960° C. Proofed at 222,500 lb.				
Shot No.	Type of Link	Location	Type	No. of Drops	Shot No.	Type of Link	Location	Type	No. of Drops	Shot No.	Type of Link	Location	Type	No. of Drops
1207	C	W	S&S	4	1001	C	W	WW	68	1026	E	W	S&S	4
1002	E	W	S&S	15	1021	C	NB	NB	100	1007	C	W	S&S	4
1000	E	W	WW	62	1063	C	NB	NB	100	1003	E	W	S&S	19
1059	E	W	S&S	82	1003	C	NB	NB	100	998	C	W	S&S	6
1020	E	W	S&S	13	987	C	NB	NB	100	1021	E	W	S&S	6
Average.....				35.2					93.6					7.8

NOTE.—"E" links are without stud.
"C" links have stud.

W = Welded end. B = Bent end. S&S = Sharp and short. WW = With weld. NB = No break.

DISCUSSION

Effect of Proofing.—The figures in the tables indicate that annealed chain proofed once is definitely weakened in resistance to shock. The annealed links of Table III withstood an average of 31 drops to failure; when proofed once these links then broke at an average of 9 drops. In two instances the proofed links failed at three drops. Referring to the lower portion of the table, results are given for links dropped on their bent ends. Four of the five annealed links tested did not break at 100 drops, but when proofed, averaged 8 drops to failure. The other three tables show results differing only in degree of brittleness. They substantiate the general conclusion that proofing is detrimental to shock-resisting properties.

TABLE IV.—16-FT. DROP TESTS OF 1⅜-IN. CHAIN (CLOSE LINKS) FROM SERVICE CHAIN.

LINKS DROPPED ON WELDED END

As Received				Annealed at 960° C.				Annealed and Proofed at 53,400 lb.[1]				Annealed at 700° C.				Annealed at 600° C.			
	Fracture				Fracture				Fracture				Fracture				Fracture		
Link No.	Location	Type	No. of Drops	Link No.	Location	Type	No. of Drops	Link No.	Location	Type	No. of Drops	Link No.	Location	Type	No. of Drops	Link No.	Location	Type	No. of Drops
75–1	W	WW	59	75–16	NB	NB	100	75–21	W	S&S	47	75–11	NB	NB	100	75–6	W	SWW	90
2	W	S&S	22	17	NB	NB	100	22	W	WW	37	12	NB	NB	100	7	NB	NB	100
3	NB	NB	100	18	NB	NB	100	23	W&B	S&S	13	13	NB	NB	100	8	NB	NB	100
4	W	S&S	65	19	[a]	[a]	83	24	W	S&S	24	14	NB	NB	100	9	NB	NB	100
5	NB	NB	100	20	W	WW	89	25	W&B	S&S	13	15	NB	NB	100	10	NB	NB	100
Average			69				95				27				100				98

W = Welded end. B = Bent end. S&S = Sharp and short. WW = With weld. NB = No break. SWW = Slight fracture with weld.

[1] Proofed using straight pin bearing.

[a] Weld opens. Link defective; worn at end.

Effect of Annealing.—Annealing for overstrained chain appears decidedly beneficial. The data of the four tables show annealing to increase resistance to shock three to five fold. Fig. 2, showing photographs of links Nos. 20 and 27, illustrates the point strikingly. Link No. 20 fractured in six blows in the hammer test. The end of the link was not noticeably flattened. Link No. 27 annealed withstood 200 blows without failure. The photograph shows this latter link after the test in a circular shape and intact.

In a study of the tables much may be gained through observing the types of fractures and their occurrence. It may be seen that the sharp and short fracture predominates in "as received" and "proofed" links. Of the 67 links that failed in these conditions, 59 broke with a sharp and short fracture. Referring now to the annealed links, Table II shows a decrease in proportion of sharp and short fractures. Table III shows only 5 "sharp and short" fractures and 18 "with the weld" fractures.

It appears that successful results have attended all three annealing temperatures, 960° C. for ten minutes, 700° C. for one hour, and 600° C. for one hour. From a practical standpoint the low-temperature anneals offer advantages of non-scaling conditions and consequent freedom from excessive wasting away of the chain. The possibility of grain growth at these low temperatures has previously been studied in the case of proofed small links. A slight grain growth occurred at 850° C. with no grain growth at 700° C. or below.

Effect of Repeated Proof Loadings and Subsequent Annealing.—The links reported upon in Table I had previously been proofed 150,000 times. From a comparison with the other tables it appears that annealing toughens such links as effectively as those proofed only once.

Effect of Size of Link and Its Resistance to Shock.—The small links of Table IV were proofed using straight pins instead of the standard U-bolt or connecting links. Straight pins were found more severe than U-bolts.

The tests of Table IV on links as received suggest that small links are tougher under shock than are large links. This has been found to be the case with various other small links drop tested and also seems to be borne out by links that fail in service, practically no instances of small links showing a sharp and short fracture being on record.

Welded End versus Bent End.—The majority of the links reported upon in the tables were dropped on their welded ends. Fifteen links, however, were dropped on their bent ends. Eleven of these 15 links broke, each of which failed at the welded end, the end opposite the one struck. Of the 54 links in Table III, the above 15 being included, 52 broke at their welded ends while 2 failed at their bent ends. These data indicate the welded end of a wrought-iron link to be definitely weaker under shock than its bent end.

DISCUSSION

Mr. Young. MR. C. D. YOUNG.[1]—As a matter of interest in connection with this paper, in my experience in the railroad we have found it is necessary in handling links of large sizes to anneal them periodically to avoid danger of the links breaking and causing personal injury, particularly on a wreck train, and crank chains on hoists. The investigation here is borne out that repeated loadings have a crystallizing effect upon the iron in the chains and there is danger from breakage under loads even lighter than the normal loading of the chain, which, as you will see, around a wreck train would be dangerous with a large group of men working about the chain.

Mr. Doke. MR. G. E. DOKE.[2]—In line with a question that has been raised in connection with our chain specifications with reference to including a limit for phosphorus content, I should like to inquire of the author of the paper as to whether any chemical analyses were made of the links tested and also as to whether he could advise as to the possible phosphorus content.

Mr. Lutts. MR. C. G. LUTTS.—With the exception of the small links, all the iron was bought under government specifications, requiring not over 0.10 per cent of phosphorus. About five analyses were made, and they averaged around 0.07 or 0.08 per cent.

Mr. Wiggin. MR. T. H. WIGGIN.[3]—I happen to have tried a few tests, not quite similar to the author's but somewhat along the same line. These tests were made by allowing dropping weights to bring up at the end of short lengths of chain. These chains were in general small, namely, $\frac{1}{2}$ in., although a few drops were tried on large chains using weights as high as 15 tons dropped two feet. The general conclusion which the speaker drew from these tests was that the first drop gave the chain a strain which was quite similar to a proof test. In other words, the chain after the first drop was proved and thereafter its nature would presumably be the same as that of a proved chain. It so happened that in all of these tests each $\frac{1}{2}$-in. chain of one kind of iron stood 10 drops of the weight and according to the crude line of reasoning in the previous sentence, these chains after proving endured nine-tenths as much work as would one that had not been proved, because the first drop proved them and the next nine drops broke

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[1] Stores Manager, Pennsylvania Railroad System.

[2] Engineer of Materials and Equipment Tests, The New York Central Railroad Co.

[3] Consulting Engineer, New York City.

Mr. Wiggin. them. If the chain had been annealed after the first drop it would have been restored to the same condition as originally except for a slight reduction in area and a narrowing of the links.

After these chains had been tested by dropping weights and one link had been broken in each, the remaining links were given a static test in comparison with a separate length of the same chain which had never been tested. The damaged chain stood 10 to 20 per cent more than the original untested chain, showing that the effect of the repeated dropping was to increase their strength slightly for static loads, although many of the welds had partly opened and the metal had been reduced in area considerably in places.

Generally speaking, if a chain is used with a high factor of safety, annealing would seem to be the logical thing, and I think it was Mr. Lutts who called attention to the fact that large chains hammer-welded by machine for the United States Navy under his direction, required annealing before it was proved as well as after. However, many chains, in fact most of them, are used above their elastic limit almost continuously. Quarry chains and foundry chains are examples of this kind of use. They get a repeated proving in use, and if they are annealed repeatedly they become badly elongated and their length of life is less than if they are not annealed.

Apparently there is some difference in action by repeated dropping of weights on a chain made up of several links from the action in a test such as the author has conducted of dropping single links. Possibly this is due to the fact that dropping a single link puts the maximum tensile stress on the inside of the bend, that is, on the part which had received in proving the maximum compressive stress.

Mr. Lutts. MR. LUTTS.—I think undoubtedly that dropping does strengthen the chain. It appears, however, that the final strength of the chain is something other than its resistance to shock. These particular links that I have reported upon break in tension close on to three quarter of a million pounds. They also break in some instances when they are dropped once from 16 ft. That is, I point out that the things are entirely different, that although a link may be stronger after being cold worked and show a higher breaking strength, that that is no measure of its resistance to shock.

Mr. Mochel. MR. N. L. MOCHEL[1] (*by letter*).—The subject of wrought-iron chain demands the most careful attention of all who make and use chain for lifting purposes, in order to eliminate or at least minimize failures which in many cases are disastrous to life and property. We have had occasion at numerous times to examine small and large

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[1] Metallurgical Engineer, Westinghouse Electric and Manufacturing Co.

Mr. Mochel. chain links which had failed in service. Invariably we have found that normalizing at 1700° F. considerably improved the ductility and shock resistance of the material, and reduced the yield point and strength to the normal condition that one might expect in wrought iron. One example, which is about the average found, may be of interest.

A large casting was being turned over in the shop and after passing the center, a slip occured, allowing the casting to fall but being arrested in its fall by the chain as it tightened again. A 1½-in. end link and a 1¼-in. link next to it both failed under this shock or suddenly applied load. Tension and Izod specimens were cut from both, giving results as follows:

	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Average Izod, ft-lb.
1¼-in. link...	42 000	67 500	28.0	29.8	18.0
1½-in. link...	32 000	52 500	40.0	54.9	26.0

The remainder were heated through at 1700° F. and air cooled, and tension and Izod tests then gave results as follows:

	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Average Izod, ft-lb.
1¼-in. link...	29 000	51 500	42.0	46.8	43
1½-in. link...	24 000	48 000	40.0	60.0	39.5

The poorer results originally and the more marked improvement of the smaller link may possibly be explained by the fact that the smaller link was subject in service to the same stress as the larger link and the over-straining was to a greater degree. This is confirmed by the high yield point and tensile strength and the greater loss in these features. Undoubtedly such treatment improves chain links by relieving over-strain and imparting greater shock resistance.

The speaker feels that this time is very appropriate to present a matter which is somewhat analogous, that is, medium size and large crane hooks. We have been greatly interested in this matter, and as little information is available, we sent a questionnaire to four large companies who are called upon to make lifts of upward to 150 tons, inquiring as to their standard practice as regards these large crane hooks. The replies were surprising:

One used a chromium-nickel steel (3.50 per cent nickel, 1.50 per cent chromium), oil quenched and drawn, to show high physical properties, and never re-treated.

The second recommended a 3-per-cent nickel, 0.45-per-cent carbon steel, in the normalized condition, and normalized every six months. **Mr. Mochel.**

The third used nothing but straight carbon steel, 0.15 to 0.25-per-cent carbon, in the annealed condition and did not re-anneal at intervals.

The fourth used only Norway or Swedish Iron in the normalized condition (from 1700° F.) and re-normalized at regular intervals.

Here are four extremes, and each practice is recommended for apparently good and sufficient reasons. It is our opinion that this question merits our attention as well as the chain links.

THE STANDARD TEST BAR FOR CAST-IRON PIPE WITH SPECIAL REFERENCE TO ITS PROGRESSIVE DEFLECTION

By James T. MacKenzie[1]

Purpose of Investigation

Of recent years there has been evinced considerable dissatisfaction by a large body of engineers and users of cast-iron pipe with the present specifications for this product, as concerns the test bar. The A.S.T.M. Specifications for Cast-Iron Pipe (A 44 – 04)[2] demand that 2 by 1 by 26-in. bars "upon supports 24 in. apart and loaded at the center shall, for pipe 12 in. or less in diameter, support a load of 1900 lb. and show a deflection of not less than 0.30 in. before breaking; and for pipes of sizes larger than 12 in., they shall support a load of 2000 lb. and show a deflection of not less than 0.32 in." The American Water Works Association specification does not differentiate between sizes but requires all metal for pipes to conform to the single requirement of 2000 lb. and a deflection of 0.30 in. before breaking.

The principal objection to the above is that almost any cast iron when made into this bar will pass this test. One foundry will give the engineer bars that break at 3000 lb. with a deflection of 0.32 in., while another will give bars breaking at 2000 lb. with a deflection of 0.45 in., and, under present specifications, he must accept both products although the metal in the first is twice as stiff as that in the second. Such an enormous latitude is not permitted in any other product with which the writer is familiar and this work was undertaken to determine, if possible, what factors govern the stiffness of cast iron and if they are economically amenable to control by the industry.

Description of Tests

The tests comprise 113 heats of widely different analysis and origin, for each of which the standard test bar for cast-iron pipe, 2 by 1 in. in cross-section by 26 in. long, were made.

Molds were rammed of pipe foundry sand, such as is used for 4-in. pipe, and blacked with the ordinary pipe foundry blacking. They were dried for two nights in the oven used for head cores, placed on an oil core or a well-blacked fire brick and poured. In the pipe foundry, recourse was had to hand ladles holding about 25 lb. with which the iron was dipped from the top of the full four-ton ladle. The bars from cupola "S" were poured from a full 2000-lb. ladle. Bars from cupolas "O" and "C" were poured from a 200-lb. shank ladle. Cupolas "P" are the 90-in. shells in the pipe foundry. Cupola "C" is the new 72-in. shell at the special foundry, cupola "S" is the old 54-in. shell at the special foundry, and cupola "O" is the 24-in. Whiting No. O (experimental). This cupola was used to try mixtures completely outside the danger line in both directions.

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[1] Chief Chemist, American Cast Iron Pipe Co., Birmingham, Ala.

[2] 1921 Book of A.S.T.M. Standards, p. 336.

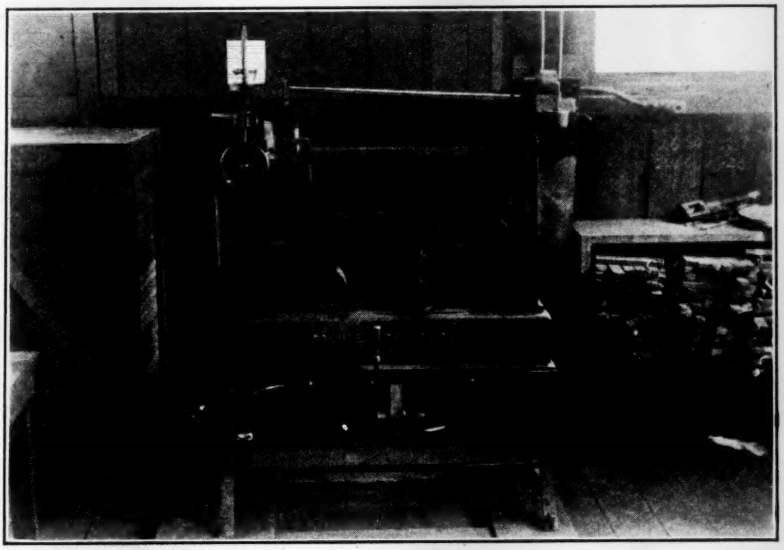


Fig. 1.—New Riehlé Motor-Driven Recording Machine for Transverse Tests.

The sets up to No. 48 were broken on an old Riehlé hand-operated testing machine using three operators. One man turned the crank, the writer balanced the beam and read deflections, while an assistant took down the readings. The vernier was set at 0.00 in. under a load of 50 lb. to be sure everything was snug. The remaining sets were broken on a new Riehlé motor-driven recording machine (Fig. 1). The machine was started some 0.05 in. above the bar to get all possible lost motion out of the deflection-recording device. Any slips due to sand on the bar, or any cause whatever, are easily seen by the break in the curve and are allowed for in the calculation of results.

The bars were marked 0.5 in. on each side of the load point and every break outside of these marks was noted as being off center.

Measurements were made at the point of application of the load with a screw micrometer reading to 0.001 in., but were reported to the nearest 0.01 in.

Table I.—Tests of Bars of Various Widths and Thicknesses Made to Test the Accuracy of the Formula $f = f_0 \frac{b\,t^3}{2}$ for Correcting Deflection at Intermediate Loads.

Thickness, in.	Width, in.	Actual Deflection, in., at		Factor	Corrected Deflection, in., at		Corrected Average Deflection, in., at	
		1500 lb.	1900 lb.		1500 lb.	1900 lb.	1500 lb.	1900 lb.
Set No. 42								
0.95	2.01	0.29	....	0.85	0.24	....	0.25	....
0.94	2.00	0.31	....	0.83	0.25	....		
0.94	2.00	0.31	....	0.83	0.25	....		
1.00	1.99	0.22	0.31	1.00	0.22	0.31	0.23	0.32
1.00	1.99	0.23	0.32	1.00	0.23	0.32		
1.01	2.00	0.22	0.31	1.03	0.23	0.32		
1.12	2.00	0.18	0.24	1.40	0.25	0.34	0.23	0.32
1.14	2.02	0.15	0.22	1.49	0.22	0.33		
1.14	2.02	0.14	0.20	1.49	0.21	0.30		
Set No. 43								
0.91	1.97	0.23	0.30	0.74	0.17	0.22	0.17	0.23
0.90	1.96	0.24	0.33	0.71	0.17	0.23		
0.91	1.97	0.24	0.32	0.74	0.18	0.23		
0.94	2.00	0.21	0.28	0.83	0.18	0.23	0.17	0.23
0.94	2.00	0.20	0.27	0.83	0.17	0.23		
0.95	2.00	0.20	0.27	0.85	0.17	0.23		
1.03	2.00	0.15	0.21	1.09	0.17	0.23	0.16	0.23
1.00	1.99	0.16	0.22	1.00	0.16	0.22		
1.02	2.00	0.15	0.22	1.06	0.16	0.23		
1.15	2.02	0.11	0.15	1.53	0.17	0.23	0.17	0.23
1.12	1.98	0.12	0.16	1.39	0.17	0.23		
1.14	2.01	0.11	0.15	1.49	0.17	0.23		
Set No. 45								
0.90	2.00	0.24	0.35	0.73	0.18	0.26	0.17	0.25
0.89	1.99	0.25	0.36	0.70	0.17	0.25		
0.90	2.00	0.23	0.35	0.73	0.17	0.25		
1.00	2.00	0.17	0.25	1.00	0.17	0.25	0.16	0.23
1.00	2.00	0.16	0.24	1.00	0.16	0.24		
0.99	2.00	0.17	0.24	0.97	0.16	0.23		
1.00	2.02	0.16	0.23	1.01	0.16	0.23		
1.00	2.01	0.16	0.24	1.00	0.16	0.24		
1.00	2.01	0.16	0.22	1.00	0.16	0.22		
1.09	2.00	0.13	0.18	1.30	0.17	0.24	0.17	0.24
1.07	1.98	0.13	0.19	1.22	0.16	0.23		
1.10	2.00	0.13	0.18	1.33	0.17	0.24		

Five bars were usually poured from each ladle of iron, and in no case does a set include two taps from a cupola. Only a few sets failed to give three good bars, these being lost chiefly from trying to take the molds or bricks out of the oven after only one night's drying.

Correction for Variation from the Standard Dimensions

The following equations were used in correcting readings to the standard bar 2 by 1 in:

$$P = \frac{2\,P_0}{b\,t^2};\quad f = f_0\,\frac{b}{2}\,t^3;\quad d = d_0\,t,$$

in which

P = breaking load in pounds,
d = deflection at breaking point, in inches,
f = deflection at intermediate points, in inches,
b = width of bar, in inches (entered in equation as pure number),
t = thickness of bar, in inches (entered in equation as pure number), and
o = observed readings.

There having been some objections made to the formula for correcting intermediate deflections, which is of course inaccurate on account of the fact that the deflection increases more rapidly than the load, wooden patterns were made of different thicknesses and bars were made under identical conditions from these patterns for comparison. Results are given in Table I and show that the formula is well within the limits of error for all but very soft metal and very large variations in thickness.

A pattern can easily be adjusted to produce a bar within 0.02 in. Large variations from the normal size for a particular pattern are especially dangerous, as oversize from thin blacking usually gives a rough bar difficult to measure accurately, and bars more than 0.02 in. under size from thick blacking are retarded in cooling to such an extent that they are entirely beyond mathematical treatment.

Materials Used

Pig irons employed were all made in the Birmingham district and included the products of the following blast furnaces:

Company	Furnace
T. C. I. & R. R. Co.	Ensley and DeBardeleben
S. S. S. & I. Co.	City and North Birmingham
Woodward Iron Co.	Woodward
Republic Iron & Steel Co.	Pioneer
Shelby Iron Co.	Shelby

TABLE II.—HEAT DATA, CHEMICAL COMPOSITION AND RESULTS OF TRANSVERSE TESTS OF 2 BY 1-IN. TEST BARS FROM 113 HEATS.

Heat Data									Chemical Composition, per cent												Results of Transverse Tests					
				Mixture, per cent																						
Set No.	Number of Bars	Cupola	Coke	Steel	Scrap	Pig	Source of Pig (Car)	Ferro-Alloys Used	Total Carbon	Graphitic Carbon	Combined Carbon	Silicon	Sulfur	Manganese	Phosphorus	Titanium	Vanadium	$C + \frac{Si}{4}$	Average Thickness of Bar, in.	Average Deflection at 1500 lb., in.	Average Deflection at 1900 lb., in.	Average Ultimate Deflection, in.	Average Breaking Load, lb.	Maximum Breaking Load, lb.
125	3	O	B	100	..	..	..	Si, Mn, L V	1.79	0.14	1.65	1.76	0.184	1.15	0.07	0.01	0.08	2.23	1.01	0.10	0.13	0.32	4620	5000
124	3	O	B	100	..	..	..	Si, Mn	1.72	0.18	1.64	2.02	0.228	0.94	0.09	0.01	0.00	2.23	1.01	0.10	0.135	0.33	4520	4780
92	4	O	A	70	..	30	P-18	Si, P, Sp	2.02	0.07	1.95	0.89	0.103	0.16	0.54	0.01	0.00	2.44	1.01	0.105	0.14	0.21	2850	3070
93	5	O	A	75	..	25	P-18	Si, P, Sp	2.13	0.04	2.09	1.59	0.111	0.22	0.80	0.01	0.00	2.52	1.01	0.11	0.14	0.18	2380	2680
88	5	O	A	50	..	50	P-18	Si, P, Sp	2.08	0.14	1.94	1.96	0.102	0.35	0.98	0.02	0.00	2.56	1.00	0.11	0.14	0.16	2130	2310
94	5	O	A	75	..	25	P-18	Si, P, Sp	2.17	1.18	0.39	2.20	0.106	0.41	0.80	0.02	0.00	2.71	1.01	0.12	0.15	0.26	3010	3260
95	4	O	A	75	..	25	P-18	Si, P, Sp	2.13	1.34	0.79	2.71	0.120	0.47	0.70	0.01	0.00	2.80	1.02	0.12	0.15	0.26	3000	3120
96	4	O	A	75	..	25	P-18	Si, P, Sp	2.23	1.32	0.91	2.46	0.117	1.33	0.97	0.02	0.00	2.81	1.00	0.12	0.15	0.25	2900	3150
114	4	O	A	100	..	..	..	Si, Mn, L V	2.74	1.78	0.96	2.05	0.121	1.30	0.05	0.02	0.26	3.25	1.01	0.12	0.16	0.36	4030	4570
86	5	O	A	40	..	60	P-18	Si, P, Sp	2.54	1.34	1.20	1.68	0.102	0.32	0.75	0.03	0.01	2.96	1.01	0.13	0.17	0.26	2900	3280
89	4	O	A	55	..	45	P-18	Si, P, Sp	2.63	1.66	0.97	1.58	0.085	0.39	0.99	0.03	0.01	3.03	1.01	0.13	0.17	0.28	2960	3370
83	9	O	A	30	..	70	P-18	Si, P, Sp	2.77	1.67	1.10	1.19	0.090	0.35	0.67	0.03	0.01	3.07	1.01	0.13	0.17	0.27	2900	3330
113	3	O	A	100	..	..	..	Si, Mn	2.48	1.65	0.83	2.94	0.111	1.60	0.05	0.02	0.00	3.14	1.02	0.13	0.17	0.26	2850	3090
137	3	O	P	..	Mal.	..	..	Si, Mn, L S	2.88	1.92	0.96	1.63	0.168	0.73	0.23	0.02	0.00	3.29	1.02	0.13	0.17	0.43	4000	4040
131	5	O	P	100	..	..	..	P	3.11	2.10	1.01	1.96	0.119	0.40	0.89	0.01	0.00	3.60	1.01	0.13	0.17	0.34	3500	3670
8	4	S	A	40	..	60	W	Sp	3.12	2.11	1.01	1.15	0.124	0.92	0.53	0.03	0.01	3.41	0.99	0.135	0.18	0.40	3380	3550
84	5	O	A	35	..	65	P-18	Si, P, Sp	2.91	2.17	0.74	1.67	0.103	0.45	0.91	0.04	0.02	3.33	1.01	0.14	0.185	0.35	3200	3480
136	4	O	P	..	Mal.	..	..	Si, Mn, L Ti	3.10	2.34	0.76	1.64	0.109	0.73	0.20	0.02	0.00	3.51	1.02	0.14	0.18	0.44	3570	3700
100	2	O	P	75	..	25	P-18	Si, Sp	3.17	2.21	0.96	1.53	0.119	0.93	0.24	0.02	0.00	3.55	1.02	0.14	0.18	0.46	3790	3940
135	4	O	P	..	Mal.	..	..	Si, Mn, L V	3.08	2.34	0.74	2.10	0.103	0.98	0.20	0.92	0.10	3.60	1.02	0.14	0.19	0.43	3600	3770

The sets are arranged in the order of increasing deflection at 1500-lb. load.

Coke.—"A," a good grade of foundry by-product coke containing 10 per cent ash and 0.6 per cent sulfur.
"P," the Barrett Company Queen Bee Coke made from coal-tar pitch and containing 0.5 per cent ash and 0.4 per cent sulfur.
"B," a hard beehive coke containing 17 per cent ash and 1.7 per cent sulfur.

Pig.—The source of pig iron is indicated simply by designation of car used. Mixtures of more than 2 cars are marked "M" and no two "M's" are the same. With this exception, all sets carrying the same car designation are made from the same pig.

Scrap.—Mal. = malleable iron. Ingot molds were used for scrap in Set No. 14.

Ferro-Alloys.—Si = 50-per-cent ferro-silicon; Mn = 80-per-cent ferro-manganese; V = 30-per-cent ferro-vanadium; P = 20-per-cent ferro-phosphorus; Ti = 25-per-cent ferro-titanium; Sp = 20-per cent spiegel; S = sulfur added as roll brimstone; L = additions in ladle; all other additions were included in the cupola charge.

TABLE II.—HEAT DATA, CHEMICAL COMPOSITION AND RESULTS OF TRANSVERSE TESTS OF 2 BY 1-IN. TEST BARS FROM 113 HEATS (*Continued*).

Heat Data									Chemical Composition, per cent											Results of Transverse Tests				
Set No.	Number of Bars	Cupola	Coke	Mixture, per cent			Source of Pig (Car)	Ferro-Alloys Used	Total Carbon	Graphitic Carbon	Combined Carbon	Silicon	Sulfur	Manganese	Phosphorus	Titanium	Vanadium	$C + \frac{Si}{4}$	Average Thickness of Bar, in.	Average Deflection at 1500 lb., in.	Average Deflection at 1900 lb., in.	Average Ultimate Deflection, in.	Average Breaking Load, lb.	Maximum Breaking Load, lb.
				Steel	Scrap	Pig																		
80	5	O	A	20	..	80	P-18	Si, P, Sp.........	2.97	2.23	0.74	1.68	0.109	0.41	0.89	0.04	0.01	3.39	1.01	0.145	0.18	0.36	3200	3400
82	5	O	A	25	..	75	P-18	Si, P, Sp.........	2.90	2.07	0.83	1.75	0.095	0.38	0.66	0.04	0.01	3.34	1.01	0.145	0.19	0.38	3490	3530
81	4	O	A	25	..	75	P-18	Si, P, Sp.........	2.99	2.22	0.77	1.65	0.104	0.42	1.04	0.04	0.02	3.40	1.01	0.145	0.19	0.33	3040	3190
2	5	S	A	40	..	60	P	....	3.14	2.02	1.12	1.14	0.085	0.31	0.64	0.03	0.02	3.42	0.99	0.145	0.19	0.41	3410	3520
6	4	S	A	40	40	20	S-1	....	3.17	2.00	1.17	1.10	0.115	0.33	0.51	0.04	0.02	3.44	0.99	0.145	0.19	0.36	2970	3060
134	4	O	P	..	Mal.	..	..	Si, Mn, L Mn.....	3.33	2.40	0.93	1.34	0.126	0.82	0.21	0.01	0.00	3.77	1.01	0.15	0.205	0.48	3540	3760
19	4	S	A	40	40	20	S-1	Si................	2.98	2.23	0.75	2.33	0.106	0.42	0.57	0.05	0.03	3.56	1.00	0.15	0.205	0.38	2980	3160
129	2	O	P	100	..	..	..	Si, Mn, L S......	3.45	2.24	1.21	1.20	0.266	0.52	0.18	0.01	0.00	3.75	1.01	0.155	0.20	0.37	3000	3120
130	4	O	P	100	..	..	..	Si, Mn...........	3.28	2.48	0.80	1.70	0.130	0.48	0.16	0.01	0.00	3.70	1.00	0.155	0.20	0.44	3310	3510
20A	3	S	A	50	..	50	S-1	Si, Sp...........	2.88	2.16	0.72	2.83	0.089	0.74	0.55	0.05	0.02	3.59	0.98	0.16	0.21	0.36	2740	2950
9	8	S	A	40	40	20	SY	Sp...............	3.31	2.29	1.02	1.37	0.108	0.39	0.51	0.04	0.02	3.65	0.99	0.16	0.21	0.44	3320	3440
37	5	S	A	30	30	40	W-2	....	3.32	2.35	0.97	1.57	0.090	0.32	0.68	0.04	0.02	3.71	0.99	0.16	0.21	0.33	2630	2700
38	4	S	A	30	30	40	W-2	....	3.31	2.27	1.04	1.40	0.095	0.31	0.72	0.04	0.02	3.66	1.00	0.16	0.22	0.33	2520	2670
45	6	S	A	20	40	40	W	Sp...............	3.35	2.35	1.00	1.32	0.106	0.39	0.72	0.04	0.02	3.68	1.00	0.16	0.22	0.42	2900	3120
36	4	S	A	30	30	40	W-2	....	3.30	2.33	0.97	1.65	0.075	0.34	0.76	0.05	0.03	3.71	1.00	0.16	0.22	0.36	2660	2700
43	3	S	A	40	20	40	W	....	3.38	2.52	0.86	1.20	0.088	0.31	0.66	0.04	0.02	3.68	1.02	0.16	0.23	0.38	2660	2810
7	5	S	A	40	40	20	S-1	....	3.28	2.07	1.21	1.30	0.105	0.27	0.58	0.04	0.02	3.61	1.00	0.165	0.22	0.38	2840	3060
107	3	O	P	100	..	..	..	Si, Mn, L V......	3.38	2.55	0.83	2.25	0.092	0.61	0.02	0.02	0.21	3.93	1.01	0.17	0.22	0.44	3200	3220
35	6	S	A	30	30	40	W-2	....	3.29	2.49	0.80	1.41	0.103	0.31	0.73	0.05	0.02	3.64	1.00	0.17	0.23	0.35	2610	2800
4	3	S	P	40	60	..	..	....	3.42	2.32	1.10	1.35	0.080	0.28	0.68	0.04	0.03	3.76	0.98	0.17	0.23	0.38	2700	2730
5	4	S	A	40	40	20	S-1	....	3.42	2.47	0.95	1.58	0.071	0.34	0.69	0.04	0.03	3.84	0.99	0.17	0.23	0.41	2840	2900
89	4	S	A	30	30	40	W-2	....	3.38	2.41	0.97	1.56	0.092	0.34	0.94	0.05	0.03	3.67	1.00	0.175	0.23	0.38	2640	2690
20B	3	S	A	50	..	50	S-1	Si, Sp...........	3.10	2.20	0.90	2.41	0.089	0.65	0.57	0.06	0.03	3.70	0.99	0.175	0.23	0.39	2700	2800
78	5	O	A	10	..	90	P-18	Si, P, Sp.........	3.40	2.76	0.64	1.89	0.083	0.44	0.80	0.05	0.03	3.87	1.01	0.175	0.23	0.33	2490	2640
55	4	O	A	..	..	100	P-18	P................	3.34	2.80	0.54	1.83	0.062	0.45	1.36	0.05	0.03	3.79	0.99	0.175	0.24	0.27	2100	2160
16	4	S	P	50	..	50	S-1	....	3.24	2.49	0.75	1.73	0.078	0.53	0.51	0.05	0.03	3.67	1.00	0.18	0.24	0.40	2710	2970
3	4	S	A	50	..	50	S-1	....	3.30	2.43	0.87	1.73	0.070	0.49	0.65	0.05	0.03	3.73	0.99	0.18	0.24	0.39	2650	2710
79	5	O	A	15	..	85	P-18	Si, P, Sp.........	3.28	2.59	0.69	1.91	0.082	0.46	0.96	0.04	0.02	3.76	1.02	0.18	0.24	0.36	2560	2640
1	6	S	P	40	..	60	W	....	3.49	2.58	0.91	1.22	0.079	0.34	0.62	0.04	0.02	3.80	1.00	0.18	0.24	0.42	2740	2970
76	5	O	A	5	..	95	P-18	Si, P, Sp.........	3.41	2.68	0.73	1.89	0.072	0.51	0.82	0.05	0.03	3.88	1.01	0.19	0.25	0.34	2430	2560

TABLE II.—HEAT DATA, CHEMICAL COMPOSITION AND RESULTS OF TRANSVERSE TESTS OF 2 BY 1-IN. TEST BARS FROM 113 HEATS (*Continued*).

Heat Data									Chemical Composition, per cent										Average Thickness of Bar, in.	Results of Transverse Tests				
Set No.	Number of Bars	Cupola	Coke	Mixture, per cent			Source of Pig (Car)	Ferro-Alloys Used	Total Carbon	Graphitic Carbon	Combined Carbon	Silicon	Sulfur	Manganese	Pho-phorus	Titanium	Vanadium	$C + \frac{Si}{4}$		Average Deflection at 1500 lb., in.	Average Deflection at 1900 lb., in.	Average Ultimate Deflection, in.	Average Breaking Load, lb.	Maximum Breaking Load, lb.
				Steel	Scrap	Pig																		
32	5	S	P	30	30	40	W-1		3.42	2.51	0.91	1.42	0.100	0.29	0.75	0.05	0.03	3.78	1.00	0.19	0.26	0.40	2540	2780
24	3	S	A	4	26	70	M		3.40	2.76	0.64	1.58	0.071	0.42	0.76	0.05	0.02	3.80	0.99	0.19	0.26	0.43	2620	2740
10	7	P	A	..	...	100	S-1 W		3.45	2.95	0.50	1.56	0.050	0.52	0.72	0.05	0.04	3.84	1.00	0.19	0.26	0.30	2070	2300
62	5	O	A	..	..	100	P-18	P	3.41	2.80	0.61	1.87	0.067	0.56	1.30	0.05	0.03	3.88	0.98	0.195	0.27	0.33	2140	2300
31	3	S	P	30	30	40	W-1		3.50	2.72	0.78	1.24	0.082	0.23	0.68	0.04	0.02	3.81	1.00	0.20	0.27	0.39	2480	2560
15	5	S	P	50	..	50	S Y	Si, Sp	3.30	2.58	0.72	2.14	0.093	0.57	0.34	0.03	0.02	3.84	1.00	0.20	0.27	0.41	2580	2780
28	4	S	A	..	25	75	W	L Ti	3.48	2.86	0.62	1.53	0.084	0.31	0.99	0.05	0.03	3.86	1.00	0.20	0.27	0.36	2300	2410
53	5	P	A	..	20	80	M		3.63	2.97	0.66	1.36	0.052	0.33	0.77	0.04	0.02	3.97	0.99	0.20	0.27	0.32	2120	2300
68	5	O	A	..	..	100	P-18	L Mn	3.50	2.89	0.61	1.93	0.065	0.85	0.8	0.06	0.03	3.98	1.00	0.20	0.27	0.31	2100	2140
34	4	S	P	30	30	40	W-1		3.52	2.72	0.80	1.40	0.085	0.28	0.75	0.04	0.02	3.86	1.00	0.20	0.28	0.33	2120	2180
67	4	O	A	..	..	100	P-18	L, Mn	3.53	2.85	0.68	1.95	0.065	1.28	0.80	0.07	0.04	4.02	1.00	0.205	0.275	0.30	2020	2050
138	4	P	A	..	20	80	M		3.58	3.06	0.52	1.78	0.064	0.45	0.82	0.05	0.03	4.04	1.00	0.205	0.285	0.38	2300	2370
139	2	P	A	..	20	80	M	L Ti	3.57	3.07	0.50	1.71	0.068	0.45	0.82	0.06	0.03	4.00	1.01	0.21	0.285	0.33	2140	2200
122	4	O	B	..	..	100	P-18		3.53	2.83	0.70	1.97	0.075	0.55	0.83	0.05	0.03	4.02	1.02	0.21	0.275	0.31	2070	2160
77	5	C	A	..	40	60	M		3.60	2.78	0.82	1.62	0.072	0.26	0.81	0.04	0.02	4.01	1.02	0.21	0.28	0.31	2000	2030
66	3	O	A	..	..	100	P-18		3.46	2.77	0.69	2.05	0.070	0.54	0.8	0.06	0.03	3.93	1.00	0.21	0.28	0.31	2040	2200
12	6	P	A	..	..	100	S Sy		3.55	2.88	0.67	1.54	0.086	0.57	0.52	0.04	0.02	3.94	1.00	0.21	0.28	0.37	2300	2450
33	5	S	P	30	30	40	W-1		3.54	2.65	0.89	1.52	0.080	0.26	0.81	0.05	0.03	3.92	1.00	0.21	0.29	0.37	2220	2300
54	4	O	A	..	..	100	P-18		3.45	2.86	0.59	1.82	0.079	0.52	0.81	0.05	0.03	3.91	0.98	0.21	0.29	0.31	1990	2090
25	2	P	A	..	25	75	D		3.52	2.83	0.69	1.67	0.070	0.64	0.76	0.06	0.03	3.94	1.00	0.21	0.29	0.42	2380	2400
11	4	P	A	..	10	90	S-1 W		3.62	3.00	0.62	1.53	0.068	0.46	0.73	0.04	0.03	4.00	1.00	0.21	0.29	0.32	2060	2120
51	5	O	A	..	..	100	P-10		3.44	2.73	0.71	2.32	0.067	0.49	0.76	0.05	0.05	4.00	1.00	0.21	0.29	0.32	2070	2080
61	5	O	A	..	..	100	P-18		3.53	2.88	0.65	1.96	0.067	0.50	0.8	0.06	0.04	4.02	1.00	0.21	0.29	0.32	2140	2170
18	6	S	P	..	..	100	PO		3.51	2.80	0.71	1.76	0.081	0.38	0.78	0.05	0.03	3.95	1.00	0.21	0.30	0.40	2230	2370
26	4	P	A	..	25	75	M		3.55	2.92	0.63	1.62	0.056	0.37	0.86	0.05	0.03	3.96	1.00	0.21	0.30	0.43	2370	2370
27	4	P	A	..	25	75	M		3.55	2.91	0.64	1.62	0.054	0.40	0.85	0.06	0.02	3.96	1.00	0.21	0.30	0.40	2240	2290
58	4	O	A	..	..	100	P-18		3.52	2.84	0.68	1.87	0.067	0.48	0.8	0.05	0.02	3.99	1.00	0.215	0.29	0.32	2030	2050
63	5	O	A	..	..	100	WF		3.50	2.02	1.48	1.80	0.118	0.21	0.84	0.05	0.02	3.95	0.99	0.22	...	0.26	1700	1790
50	5	O	A	..	..	100	P-10		3.41	2.80	0.61	2.48	0.073	0.49	0.81	0.07	0.05	4.03	1.00	0.22	0.29	0.34	2100	2180
23	5	P	A	4	26	70	M		3.46	2.76	0.70	1.86	0.070	0.44	0.79	0.05	0.03	3.94	1.00	0.22	0.30	0.42	2300	2300

TABLE II.—HEAT DATA, CHEMICAL COMPOSITION AND RESULTS OF TRANSVERSE TESTS OF 2 BY 1-IN. TEST BARS FROM 113 HEATS (*Continued*).

Heat Data									Chemical Composition, per cent											Results of Transverse Tests				
				Mixture, per cent																				
Set No.	Number of Bars	Cupola	Coke	Steel	Scrap	Pig	Source of Pig (Car)	Ferro-Alloys Used	Total Carbon	Graphitic Carbon	Combined Carbon	Silicon	Sulfur	Manganese	Phosphorus	Titanium	Vanadium	$C + \frac{Si}{4}$	Average Thickness of Bar, in.	Average Deflection at 1500 lb., in.	Average Deflection at 1900 lb., in.	Average Ultimate Deflection, in.	Average Breaking Load, lb.	Maximum Breaking Load, lb.
52	4	O	A	..	40	60	P-10	....	3.40	2.67	0.73	2.12	0.086	0.40	0.79	0.05	0.03	3.94	1.00	0.22	0.30	0.34	2070	2180
118	3	O	A	..	..	100	P-18	....	3.46	2.81	0.62	1.95	0.066	0.50	0.8	0.06	0.03	3.95	1.02	0.22	0.30	0.38	2230	2350
59	5	O	A	..	..	100	P-18	....	3.40	2.84	0.56	2.30	0.064	0.49	0.77	0.07	0.04	3.98	1.00	0.22	0.30	0.35	2100	2130
140	4	P	A	4	20	76	M	....	3.57	2.91	0.66	1.65	0.070	0.43	0.73	0.05	0.03	3.98	1.01	0.22	0.30	0.35	2070	2300
141	4	P	A	4	20	76	M	L S........	3.57	2.85	0.72	1.65	0.110	0.44	0.76	0.05	0.03	3.98	1.01	0.22	0.30	0.35	2080	2180
17	3	S	P	..	..	100	W	....	3.53	2.77	0.76	1.58	0.064	0.22	0.74	0.04	0.04	3.93	1.00	0.22	0.31	0.38	2100	2290
30	3	S	A	..	40	60	W	....	3.57	2.91	0.66	1.90	0.063	0.30	0.84	0.05	0.02	4.05	1.00	0.22	0.31	0.38	2170	2210
115	4	P	A	..	20	80	M	....	3.59	2.91	0.68	1.70	0.059	0.42	0.79	0.05	0.03	4.02	1.01	0.22	0.315	0.40	2200	2260
57	3	O	A	..	..	100	P-18	....	3.51	2.85	0.66	1.95	0.070	0.50	0.84	0.05	0.04	4.00	1.00	0.225	0.31	0.36	2100	2220
42	3	S	A	..	..	100	S-2	....	3.33	2.82	0.51	3.16	0.061	0.32	0.84	0.13	0.05	4.12	1.00	0.23	0.32	0.38	2140	2170
49	6	S	P	..	..	100	E	....	3.63	3.05	0.58	1.92	0.051	0.42	0.78	0.05	0.05	4.11	1.00	0.23	0.32	0.43	2260	2270
48	4	P	A	4	26	70	M	....	3.53	2.74	0.79	1.62	0.073	0.41	0.83	0.04	0.03	3.94	0.99	0.23	0.32	0.41	2200	2280
99	5	C	A	3	22	75	M	....	3.71	2.95	0.76	1.84	0.070	0.36	0.79	0.07	0.04	4.17	1.03	0.23	0.33	0.39	2070	2140
41	5	S	A	..	..	100	D-1	....	3.72	2.88	0.84	1.50	0.054	0.41	0.91	0.05	0.03	4.10	1.00	0.24	0.33	0.40	2100	2130
119	2	O	A	..	..	100	P-18	....	3.65	2.92	0.73	1.94	0.055	0.60	0.8	0.06	0.03	4.14	1.02	0.24	0.33	0.41	2170	2280
126	4	O	B	..	..	100	S Y	....	3.52	2.88	0.64	2.19	0.082	0.64	0.42	0.03	0.01	4.07	1.01	0.24	0.34	0.42	2100	2220
120	3	O	A	..	..	100	P-18	L S........	3.48	2.90	0.58	1.94	0.136	0.53	0.81	0.06	0.03	4.07	1.02	0.245	0.335	0.42	2150	2230
116	5	C	A	3	22	75	M	....	3.63	2.88	0.75	1.83	0.077	0.34	0.76	0.08	0.04	4.09	1.02	0.255	0.355	0.42	2030	2150
127	2	O	A	..	..	100	S Y	....	3.51	2.99	0.52	2.20	0.084	0.64	0.40	0.05	0.02	4.06	1.00	0.26	0.36	0.43	2060	2070
121	5	O	A	..	..	100	P-18	L S........	3.59	2.74	0.85	2.16	0.194	0.52	0.8	0.06	0.03	4.13	1.02	0.26	0.36	0.42	2080	2130
40	6	S	P	..	..	100	P-7	....	3.69	2.93	0.76	2.00	0.061	0.56	0.80	0.07	0.04	4.19	1.00	0.27	0.37	0.44	2070	2200
128	4	O	A	..	..	100	S Y	L S........	3.54	2.81	0.73	2.36	0.107	0.56	0.47	0.05	0.01	4.13	1.00	0.27	0.38	0.40	1940	2000
117	5	O	P	..	..	100	P-18	....	3.67	3.05	0.62	1.92	0.060	0.53	0.82	0.06	0.04	4.15	1.02	0.275	0.40	0.44	2000	2080
46	3	S	A	..	..	100	S-1	....	3.45	2.65	0.80	2.96	0.042	0.84	0.77	0.10	0.05	4.19	0.98	0.28	0.38	0.42	2000	2060
29	7	S	P	..	..	100	S Y	P........	3.57	2.82	0.75	2.20	0.078	0.62	1.12	0.06	0.02	4.12	1.00	0.285	0.41	0.42	1940	2020
108	3	O	P	100	..	..	..	Si, Mn........	3.27	2.60	0.67	3.76	0.077	1.35	0.04	0.02	0.00	4.21	1.03	0.285	0.41	0.42	1950	1980
106	2	O	P	..	..	100	W-4	....	3.77	3.10	0.67	1.36	0.029	0.35	0.82	0.06	0.03	4.11	1.00	0.29	0.42	0.42	1880	1930
104	3	O	P	..	..	100	S-3	....	3.93	3.27	0.66	1.30	0.027	0.31	0.70	0.06	0.03	4.26	1.03	0.32	....	0.44	1790	1810
14	4	S	P	..	50[a]	50	S Y	....	3.77	3.27	0.50	1.88	0.069	0.72	0.36	0.04	0.02	4.24	1.00	0.33	0.50	0.56	2020	2190
110	2	O	P	..	..	100	S-4	L-1.5 per cent Steel	3.72	3.00	0.72	2.04	0.026	0.25	0.8	0.08	0.04	4.23	1.01	0.35	....	0.44	1620	1630
109	3	Q	P	..	..	100	S-4	....	3.73	3.01	0.72	2.09	0.025	0.25	0.83	0.08	0.03	4.25	1.01	0.355	....	0.44	1650	1710
13	4	S	P	..	..	100	S Y	....	3.73	3.20	0.53	2.34	0.061	0.80	0.45	0.05	0.02	4.32	1.00	0.36	0.55	0.60	2000	2080
105	3	O	P	..	..	100	S-3	....	3.95	3.33	0.62	1.54	0.033	0.29	0.72	0.06	0.03	4.44	1.02	0.37	....	0.49	1720	1790

[a] Ingot Molds.

The Shelby iron was made in the Shelby charcoal furnace while running on coke, and is mentioned especially in view of the fact that it carried a load of 2000 lb. with a deflection of 0.61 in. at the breaking point (set No. 13).

Referring to Table II, broken pipe was the only scrap used called "scrap"; miscellaneous steel scrap is included under the designation "steel." Ingot mold scrap was used in one set (No. 14), and malleable iron in the sets Nos. 134 to 137, inclusive. Ferro-alloys used were 20-per-cent spiegel, 80-per-cent ferro-manganese, 30-per-cent ferro-vanadium, 20-per-cent ferro-phosphorus, 50-per-cent ferro-silicon and 25-per-cent ferro-titanium. In Table II, the elements indicated by their chemical symbols are to be interpreted as being added in the form of the ferro-alloys mentioned above; except spiegel, which is abbreviated Sp., and sulfur, which was added as roll brimstone. Ladle additions are preceded by the letter L; all others were included in the cupola charge.

The pigs used are indicated by the column marked "Car" in Table II where each car used is designated. Mixtures of more than two cars are marked "M," and no two "M's" are the same. With this exception all sets carrying the same car designation are made from the same pig.

Three cokes were used: "A" a good grade of foundry by-product coke containing 10 per cent ash and 0.6 per cent sulfur; "P," the Barrett Company's "Queen Bee" coke made from coal-tar pitch and containing 0.5 per cent ash and 0.4 per cent sulfur; and "B," a very hard beehive coke containing 17 per cent ash and 1.7 per cent sulfur.

Sampling and Analysis.—All samples were taken from the most representative bar of the set. The bar was ground clean not more than 2 in. from the point of rupture and a $\frac{7}{8}$-in. drill driven completely through the center of it, the drillings being caught on a clean piece of heavy paper. No further comminution of the sample was attempted.

Silicon was run by the nitro-sulfuric acid method and checked at least once, and in some cases more often if the results were more than 0.04 per cent apart.

Sulfur was run by the evolution method and checked by the oxidation method, the latter results only being given. Manganese was run by the persulfate-arsenite method and the first 49 sets were checked by the bismuthate-arsenite, but the difference did not warrant the greater trouble involved so the bismuthate method was discontinued thereafter.

Phosphorous was run by the alkali-acid titration method. It was not run on some of the melts from the car P-18, and is given in the tables as 0.80 per cent, as the greatest variation found was from 0.78 to 0.82 per cent.

Titanium and vanadium were run from the same sample, the procedure being as follows: Dissolve 5 g. in 30-per-cent HCl and filter. Burn off graphite in platinum crucible, volatilize silica with HF and H_2SO_4, evaporate and ignite. Fuse the residue with sodium carbonate, dissolve in water and filter off P and Va. Return the residue to the crucible, burn off paper and fuse with $KHSO_4$, dissolve in 10-per-cent H_2SO_4, cool, add H_2O_2, and compare for titanium. Acidulate the filtrate with H_2SO_4 and add about 5 per cent excess. Add H_2O_2 and compare with the standard iron similarly treated for vanadium.

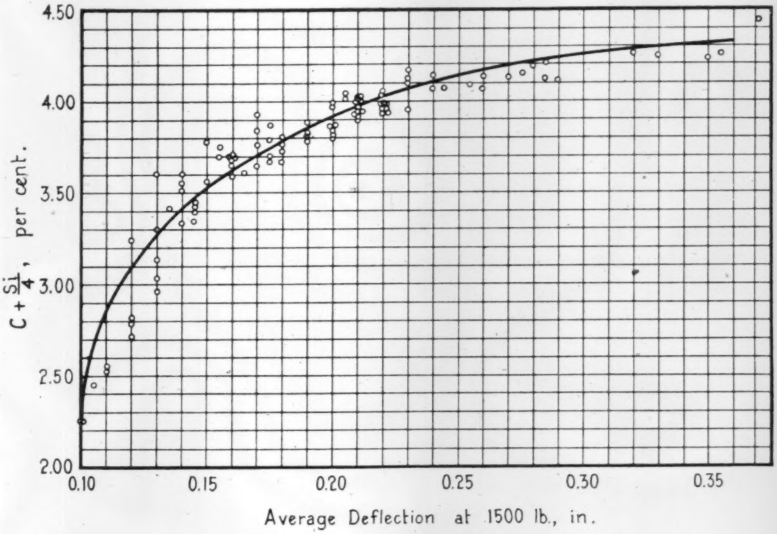


Fig. 2.—Relation Between Carbon plus One-fourth Silicon (C + Si/4) and Deflection at 1500-lb. Load.

Carbons were determined by direct combustion in clay boats, using iron oxide as a lining material; and the carbon dioxide was absorbed by ascarite in a Nesbitt bulb. A zinc tower and a phosphorous tower were used after the reduced end silica tube. The high-sulfur irons were checked with a chromicsulfuric acid bulb in place of the zinc. Only a very high sulfur appears to get through a column of fresh zinc. Sample No. 121 with 0.194 per cent sulfur showed a drop of 0.05 per cent carbon and sample No. 129 with 0.266 per cent sulfur showed a drop of 0.07 per cent carbon as between the two materials, the possible error on No. 129 being 0.15-per-cent carbon or $\frac{6}{11}$ of the sulfur

Graphite was run with every precaution known, but the combined carbon calculated from it could not be brought into agreement with the microscope in many cases. Standard samples were always used at the beginning and at the end of the run. Standard sample No. 7*a*, graphite 1.98 per cent, was used for this purpose and in no case were the results off more than 0.05 per cent, but the samples themselves still show an unreasonable amount of combined carbon in many instances. Some of the high-graphite iron was checked by rubbing down half the sample in a mortar, blowing most of the loose graphite out and running graphite and total carbon on the blown sample as against the original, hoping to get the combined carbon in this way. The results were unsatisfactory as follows:

		Total Carbon, per cent	Graphitic Carbon, per cent	Combined Carbon, per cent
Set No. 13	Original	3.73	3.21	0.52
		3.71	3.18	0.53
	Blown	3.27	2.60	0.67
		3.23	2.56	0.67
Set No. 53	Original	3.62	2.97	0.65
		3.64	2.98	0.66
	Blown	3.50	2.83	0.67
Set No. 106	Original	3.79	3.15	0.64
		3.76	3.04	0.72
	Blown	3.37	2.70	0.67
Set No. 119	Original	3.67 3.63	2.92	0.73
	Blown	3.43	2.82	0.61

The question arises as to whether all the carbon in cast iron is always present as graphite and combined carbon. A great number of the samples were run by the color method for combined carbon. They seem to indicate that there is not as much combined carbon present as the total minus graphite gives, but the results were so erratic as to be unfit for publication.

Results of Tests

The results of the tests are shown in Table II which gives in the order of the deflection at 1500 lb.: The number of bars, cupola, coke, mixture; average thickness, average deflections at 1500 lb., at 1900 lb., and at breaking point, average breaking load and maximum breaking load. Custom requires that the average be given, but inasmuch as it is practically impossible to make a perfect test bar, the best is probably still short of the possibilities of a particular iron. Chemical composition is given for each set and an attempt is made to

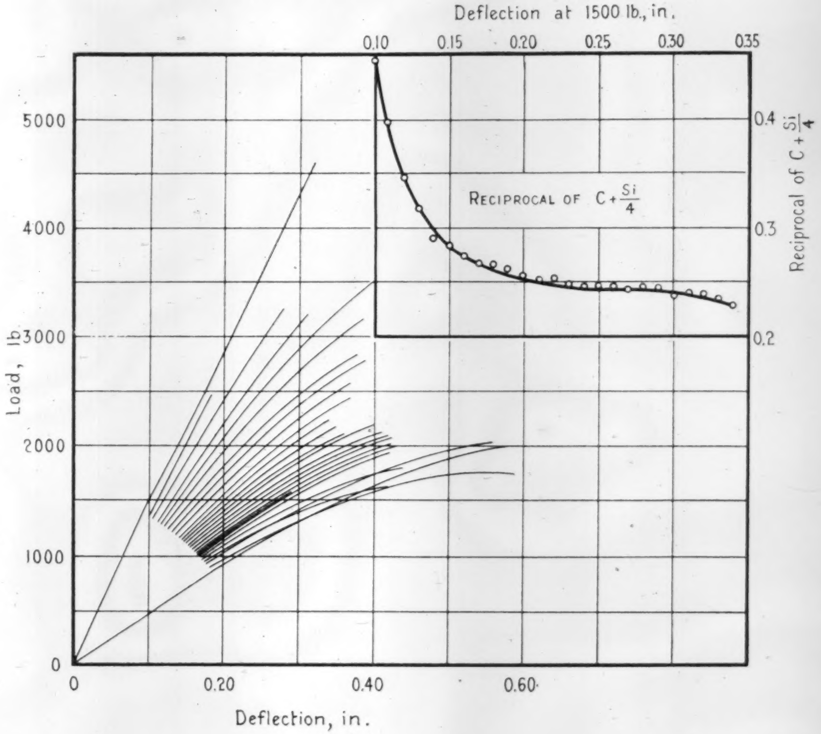


Fig. 3.—Composite Load-Deflection Curves for each 0.01 in. Deflection at 1500 lb. Showing also the Reciprocal of C + Si/4 for the Corresponding Groups Plotted Against Deflection at 1500-lb. Load.

reconcile the composition and the deflection by adding the total carbon and one-fourth of the silicon. Fig. 2 shows the C+Si/4 plotted against the deflection at 1500 lb. Fig. 3 shows composite graphs of load-deflection curves grouped for all the bars, for each 0.01-in. deflection at 1500 lb.; with the reciprocal of the average of C+Si/4 for these groups plotted against the deflection at 1500 lb., shown in the upper right corner.

Discussion of Results

It is apparent that up to 0.17 in. deflection at 1500 lb. or 0.23 in. deflection at 1900 lb., the rise in C+Si/4 with the deflection is quite rapid and uniform, but beyond this point it is slow and erratic. Many combinations were tried, especially with phosphorous, as in at least two instances this element seemed to cut the deflection sharply; namely, No. 29, deflection 0.285 in., from the same pig as No. 13, deflection 0.36 in., with ferro-phosphorous melted with it; and No. 55, deflection 0.175 in., from the same pig as No. 54, deflection 0.21 in., similarly treated. However, the carbon dropped on both melts and a repeat on No. 55, No. 62, brought the deflection back to 0.195 in., but the carbon was still low. Set No. 131, an all-steel heat with 0.89 per cent phosphorus, is much the highest C+Si/4 shown for its deflection of 0.13 in.; but set No. 114, deflection 0.12 in., is equally high with phosphorus content of only 0.05.

Table III.—Effect of Sulfur on Deflections.

Heat	Set No.	Deflection at 1500 lb., in.	C + Si/4, per cent	Sulfur, per cent
3/21	119	0.24	4.14	0.055
	120[a]	0.245	4.07	0.136
	121[a]	0.26	4.13	0.194
3/29	127	0.26	4.06	0.084
	128[a]	0.27	4.13	0.107
3/30	129[a]	0.155	3.75	0.266
	130	0.155	3.70	0.130
4/5	134	0.15	3.77	0.126
	135	0.14	3.60	0.103
	136	0.14	3.51	0.109
	137[a]	0.13	3.29	0.168
4/22	140	0.23	3.98	0.070
	141[a]	0.23	3.98	0.110

[a] Roll brimstone added.

Sulfur is shown, by the data in Table III, to have no influence on the deflection. In this table, each heat represents two or more consecutive ladles tapped in the order of the set numbers, with roll brimstone added to sets Nos. 120, 121, 128, 129, 137 and 141.

Manganese is seen at a glance to have no bearing on this bar, though its influence in the pipe foundry is very marked.

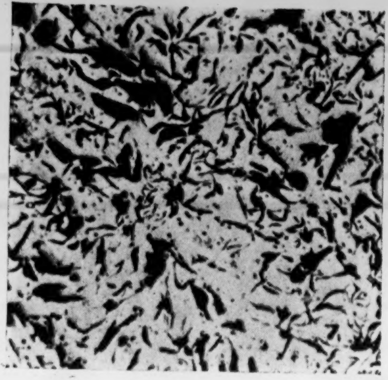
Vanadium is apparently responsible for two misplaced bars: No. 107, deflection 0.17 in., vanadium 0.21 per cent; and No. 114, deflection 0.12 in., vanadium 0.26 per cent; but 0.08 per cent vanadium did not seem to affect No. 125, deflection 0.10 in., which was, however, a white iron and badly oxidized in melting.

Titanium was tried without results but could not be found in the bar. The companion sets Nos. 26 and 27, 134 and 136, and 138 and 139 were made to test this. The second ladle mentioned in each pair had been treated with 0.8 per cent ferro-titanium, or 0.2 per cent titanium, but the greatest recovery obtained was 0.01 per cent on No. 136, over 95 per cent of it being lost with no advantage to the bar.

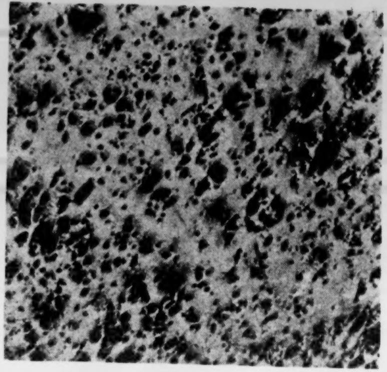
Table IV.—Effect of Temperature of Pouring upon Strength and Deflection of Test Bars.

Temperature, deg. Fahr.	Deflection at 1900 lb., in.	Ultimate Load, lb.	Ultimate Deflection, in.
2510	0.25	2580	0.36
	0.25	2730	0.40
	0.24	2560	0.35
Average	0.25	2620	0.37
2450	0.25	2550	0.36
	0.25	2770	0.40
	0.24	2520	0.35
Average	0.25	2610	0.37
2420	0.24	2670	0.36
	0.25	2510	0.36
	0.24	2650	0.37
Average	0.24	2610	0.36
2380	0.23	2500	0.34
	0.24	2370	0.33[a]
	0.25	2600	0.38
Average	0.24	2550	0.36
2340	0.23	2730	0.38
	0.26	2060	0.28[a]
	0.25	2530	0.35
Average	0.24	2630	0.36
2300	0.25	2460	0.35
	0.26	2260	0.32[a]
	0.23	2740	0.38
	0.24	2280	0.31[a]
	0.23	2430	0.32
Average	0.24	2540	0.35

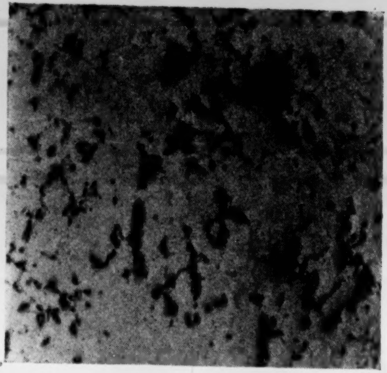
[a] Flawed, not included in average.



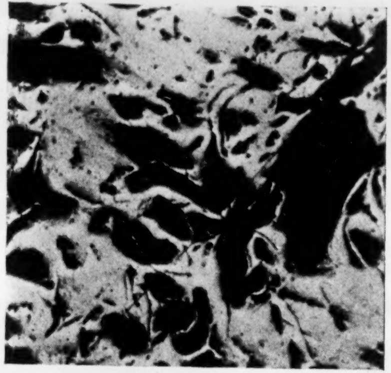
Set No. 15. Deflection at 1500 lb., 0.20 in. T.C., 3.30; G.C., 2.58; Si, 2.14; S, 0.093; Mn, 0.57; P, 0.34. Showing unusually fine, well disseminated flakes of graphite.



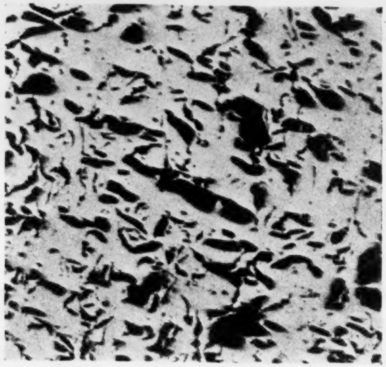
Set No. 129. Deflection at 1500 lb., 0.155 in. T.C., 3.45; G.C., 2.24; Si, 1.20; S, 0.266; Mn, 0.52; P, 0.18. Showing sulfides and fine, globular graphite.



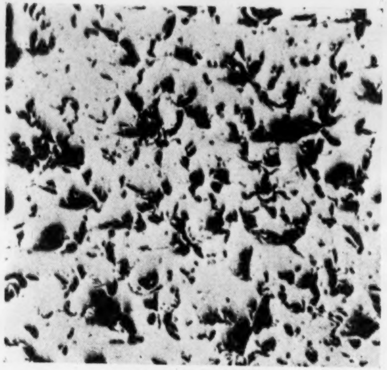
Set No. 96. Deflection at 1500 lb., 0.12 in. T.C., 2.23; G.C., 1.32; Si, 2.46; S, 0.117; Mn, 1.33; P, 0.97. Showing graphite and small sonims.



Set No. 68. Deflection at 1500 lb., 0.20 in. T.C., 3.50; G.C., 2.89; Si, 1.93; S, 0.065; Mn, 0.85; P, 0.8. Showing very coarse clusters of graphite in striking contrast to Set No. 15 of the same deflection.

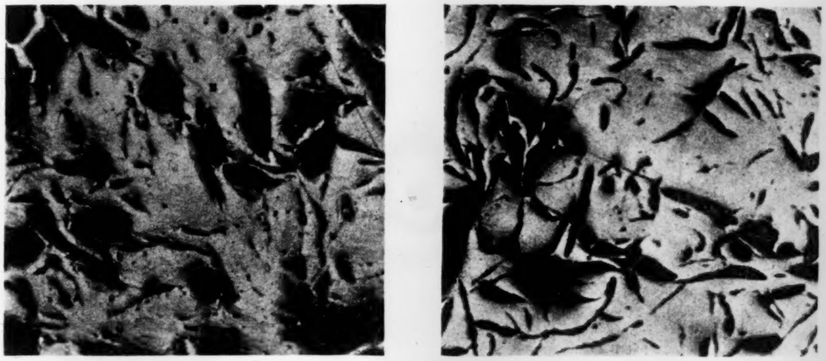


Set No. 130. Deflection at 1500 lb., 0.155 in. T.C., 3.28; G.C., 2.48; Si, 1.70; S, 0.130; Mn, 0.48; P, 0.16. Showing fine flake graphite and some few sulfide inclusions.



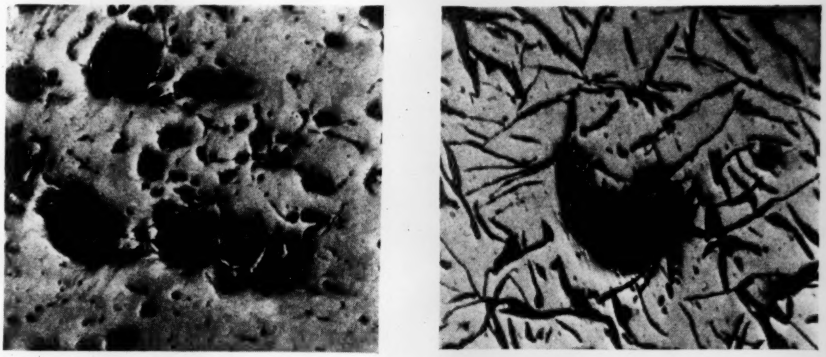
Set No. 114. Deflection at 1500 lb., 0.12 in. T.C., 2.74; G.C., 1.78; Si, 2.05; S, 0.121; Mn, 1.30; P, 0.05; V, 0.26. Showing graphite very fine and broken.

Plate I.—Photomicrographs of Bars of Representative Deflections. Unetched (× 50).



Set No. 17. Deflection at 1500 lb., 0.22 in. T.C., 3.53; G.C., 2.77; Si, 1.58; S, 0.064; Mn, 0.22; P, 0.74. Showing very coarse graphite segregations.

Set No. 30. Deflection at 1500 lb., 0.22 in. T.C., 3.57; G.C., 2.91; Si, 1.90; S, 0.063; Mn, 0.30; P, 0.84. Showing long flake graphite.



Set No. 63. Deflection at 1500 lb., 0.22 in. T.C., 3.50; G.C., 2.02; Si, 1.80; S, 0.118; Mn, 0.21; P, 0.84. Showing globular graphite and both sulfide and oxide inclusions. A very weak iron.

Set No. 13. Deflection at 1500 lb., 0.36 in. T.C., 3.73; G.C., 3.20; Si, 2.34; S, 0.061; Mn, 0.80; P, 0.45. Showing unusually complete net work of graphite.

PLATE II.—Photomicrographs of Bars of Representative Deflections. Unetched (× 50).

Every effort was made to obtain a very high carbon metal with good silicon, but it seems impossible to get it except in a low-silicon pig, which of course nullifies the effect of the carbon. The graphite rises fairly well with the deflection but as was previously stated the combined carbons are hopeless. These latter are merely incidental phenomena—the result of the same forces, chemical or physical, which control the physical properties of the iron and are of passing interest only—for the primary influences are the real points of concern.

Factors not considered in this investigation are the temperature of pouring, the condition of the cupola, and the brand and grades of metal used. That temperature has considerable influence is not at all apparent so long as the metal is fluid enough to fill the molds completely before solidification begins. This temperature, which varies largely with the carbon, is sufficient to keep the bar free from blow holes and cold shuts. One experiment was made to determine this temperature effect, and is shown in Table IV. This set is not included in Table II. The mixture was 20 per cent steel, 30 per cent scrap, and 50 per cent pig, with a little spiegel in the charge. Temperatures were read on the surface of the iron in the 2000-lb. ladle, with a disappearing filament pyrometer. Temperatures are comparative but are probably high as the iron was freezing on the ladle lip as the last set of bars was being poured. The iron was held after pouring each set until it showed a decided drop in temperature.

Table V.—Influence of Cupola Conditions on Properties of Test Bars

All bars from melts of pig P-18 (see Table II).

Heat No.	C+Si/4, per cent	Deflection, in., at		Ultimate Load, lb.	Ultimate Deflection, in.
		1500 lb.	1900 lb.		
66	3.93	0.21	0.28	2040	0.31
54	3.91	0.21	0.29	1990	0.31
61	4.02	0.21	0.29	2140	0.32
58	3.99	0.215	0.29	2030	0.32
118	3.95	0.22	0.30	2230	0.38
59	3.98	0.22	0.30	2100	0.35
57	4.00	0.225	0.31	2100	0.36
119	4.14	0.24	0.33	2170	0.41

It is not meant to infer from this test that iron melted cold in the cupola will equal the same iron melted hot. This is a question of cupola conditions and not of temperatures. That the cupola conditions are responsible for large variations in the properties of the bar is shown in the numerous melts of the car of pig P-18, which was thoroughly mixed in unloading and used as the base of most of the melts in the experimental cupola. This pig was used without additions of any kind in the heats listed in Table V.

Concerning the properties derived from different brands and qualities of pig iron, the writer is not willing to draw any conclusions from such data as have been obtained. For that reason brands have been omitted from this paper.

Photomicrographs of one bar from representative deflections are shown in Plates I and II. All are shown unetched at 50 diameters, which gives a good idea of the size, shape and distribution of graphite.

CONCLUSIONS

From the results of these tests and thousands of individual bars made from other mixtures, not so well substantiated but in the mass reliable, the writer would unhesitatingly recommend that the Society join all parties concerned in an effort to draw the lines tighter about the quality of the iron going into cast-iron pipe. To set a definite minimum for the deflection at 1900 lb. would be a long step forward. Under the present specifications the engineer would have to accept the pipe from set No. 125, which although really a high-carbon steel and so brittle that each half broke in two pieces on striking the bed-plate of the machine, still supported a load of 2000 lb. and had a deflection of over 0.30 in. There is no doubt that brittleness is the worst trouble a pipe can have. Brittle pipe break on the shake-out, in the cleaning sheds, on the loading yard, in the cars, in being unloaded, in being laid in the trench, and for years afterwards. The principal cause for brittle pipe is low carbon or low silicon or oxidation in the cupola, which is usually reflected in these two elements and the manganese. The writer is firmly convinced that most of the troubles blamed on sulfur are really caused by the quality of the material charged which carries the sulfur with it, and that the troubles blamed on low manganese are directly traceable to conditions in the melting zone of the cupola. Setting a minimum of 0.25 in. for the deflection of the bar under a 1900-lb. load would undoubtedly keep a great deal of material out of our pipe foundry cupolas that should not go into them, but would not cause any violent changes in the present practice. It would also tend to keep the industry on the alert in regard to its cupolas, which, in itself, would yield good returns.

The suggestion to specify an additional increment of deflection for each increment of load beyond 1900 lb. is entirely superfluous, as in every case the radius of curvature of the load-deflection curve tends to become smaller as the load increases. This is well illustrated by the composite graphs shown in Fig. 3.

ACKNOWLEDGMENTS

The thanks of the author are due to Mr. W. D. Moore, President of the American Cast Iron Pipe Co., for the generous allowance of time and materials necessary in this investigation; to Mr. R. R. Deas, Jr., for his hearty cooperation in the exceedingly laborious and tedious analyses; and to Mr. R. N. Stubbs, Jr., for the photomicrographic work.

[For a discussion on Cast Iron for Pipe, see page 706.—ED.]

RECENT INVESTIGATIONS ON CAST IRON FOR PIPE

By Richard Moldenke[1]

Introduction

Of recent years there have been some important developments in the art of making cast-iron pipe, and with the introduction of new methods which give castings of different structure from the regular standard, there has been added a complication in testing the metal to do justice to which will require much thought and some research. Apart from this, however, it should be stated that for a number of years the engineers of the great municipal waterworks, through their association committees, have worked in conjunction with similar committees of manufacturers of cast-iron pipe in striving to shape existing specifications to get a metal best suited to the conditions of service. In this endeavor the engineers have been somewhat hampered by unfamiliarity with the wide range of application of cast iron other than for the specific purpose of making pipe, and both engineers and pipe manufacturers must hold to a product of the lowest range of cost possible considering the magnitude of the projects involved. A study of the enormous sums involved in the execution and extension of water service lines is illuminating on this point. None the less, engineers and foundrymen have been anxious to cooperate in getting the best possible product consistent with the conditions existing, and when finally the engineers presented definite suggested changes in specification requirements, the foundrymen united in an investigation to see whether it would be possible to acquiesce.

In November, 1920, the writer was entrusted by the manufacturers of cast-iron pipe with a commission to make this investigation, and their plants were opened for study of processes and tests of materials and products. The work itself spread over two years and the final report was made on November 25, 1922. The conferences of the joint committee of engineers and manufacturers took another six months, and while much was learned of the requirements of user and producer, no definite conclusions could as yet be reached. In view of the growing importance of research work for this particular branch of the foundry industry in which engineers and foundrymen alike must participate, the manufacturers of cast-iron pipe who financed this investigation have generously released the data obtained for presentation to the American Society for Testing Materials, so that the information contained may become available generally. The writer has given this material in summarized form, but with sufficient tabular detail to illustrate the points involved.

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[1] Consulting Metallurgist, Watchung, N. J.

The existing standard specifications call for the testing of the quality of the metal going into cast-iron pipe by means of a bar 2 by 1 in. in cross-section, and 26 in. long. This bar, placed flat on supports 24 in. apart, shall be capable of sustaining a load of at least 2000 lb. before breaking, and when breaking shall show a deflection of at least 0.30 in. In practice, however, it is often very necessary to use iron mixtures which give much higher breaking loads, even up to 2800 lb., in order to get a passing deflection at rupture of 0.30 in. The engineers for the consumers, therefore, rightly claim that the character of irons which break at 2000 lb. and 0.30 in. deflection, at 2800 lb. and 0.30 in. deflection, and at 2000 lb. and 0.40 in. deflection are different and the pipe made with these irons must react differently in service; hence the proposition to set 0.30 in. as the minimum deflection for a load of 2000 lb. (finally changed to 1900 lb.) with an increase in deflection of 0.025 in. for every 200 lb. load required until rupture. In this manner the engineers expected to get a line of cast iron with the proper resilience for pipe purposes.

The results of the investigation showed that the proposed requirement just outlined would make a tremendous difference in actual pipe-making practice, that only a little over a quarter of the pipe made to-day could pass, and that the demand for 0.30 in. deflection with 1900 lb. load was almost as difficult to comply with as with 2000 lb., in view of the present day pig irons available for pipe-making purposes. Nevertheless, the manufacturers of pipe authorized the study of mixtures of iron with variations in the pig percentages, to see if it were not possible to meet the requirements desired by the engineers. The results were again not satisfactory, and the final outcome was to continue working under the existing specifications and await what light might be had on the subject when the iron industry would have readjusted itself completely to normal peace-time conditions. The recommendations of the writer in his final report are given later.

GENERAL PROGRAM OF TESTS

In laying out a program of operations, the foundrymen's committee arranged for the cooperation of four northern and four southern foundries, so that the relative performances of the two main types of

American irons for pipe-making purposes might be established. These eight foundries were duly visited by the writer and the several sets of bars to be described were arranged for. In each case sufficient time was given to make certain of the molding, pouring and cleaning of the bars under identical conditions, for it was found that in daily routine the ordinary test bars were not all made the same way at the different plants. Hence, where necessary, the practice was changed so that all bars were cast in dry-sand molds in vertical position, with top pour, brushed clean and carefully marked for identification. On shipment to the author's testing laboratory the bars were broken transversely in a Riehlé machine with specially designed recording mechanism giving test curves very accurately and on a fairly large scale.

In each foundry, provision was made to get metal suited respectively for light, medium and heavy pipe. The silicon was therefore run as nearly as convenient to 2.00, 1.75 and 1.50 per cent, the first corresponding to metal suited for fittings and light pipe, the second for medium-thickness 10 or 12-in. pipe, and the last for heavy pipe 24 in. and over in diameter. Side by side with the 2 by 1-in. pipe test bars—the standard for pipe-making—the writer had arranged for similar sets of bars of the A.S.T.M. standard arbitration test bars 1¼ in. in diameter, as it was desired to study their value for this line of foundry product.

After test, each bar was carefully calipered at the point of rupture for purposes of correction to standard, and the results tabulated. Test curves were obtained for every bar, and used for preparation of composite curves in the study of strength and deflection comparisons. The three arbitration bars of each set which came closest to standard dimensions and average test results were then selected for tension test, and the lower halves sent to Saunders and Franklin, of Providence, R. I., for analysis, the tension tests being carried out at the Brown University testing laboratory. Every precaution was taken to get reliable results, the A.S.T.M. methods for sampling and analysis being followed closely. The tension test was made to satisfy engineers more particularly, as the engineering mind generally thinks of metals and alloys in terms of their tensile strength, whereas the foundryman deals with the smaller figures involved in the transverse test.

RESULTS OF TESTS

Tests of 2 by 1-in. Standard Pipe Test Bars.—Table I gives summaries of the results of the first series of tests in the eight foundries in question. Each set was intended to have 12 bars, but this was often overrun. Through imperfections in applying the "blacking" on the molds for the bars small particles would be loosened occasionally, resulting in slight flaws in the bars at the point of rupture. All such results were thrown out, only bars perfectly sound at the rupture point being used. This table shows that the grand average of all the 2 by 1-in. bars came to 2236 lb. transverse breaking load, with a grand average of 0.360 in. in deflection. Under the specification of a breaking load of no less than 2000 lb., with a deflection of no less than 0.30 in. when breaking, the above figures indicate a rather good average. Unfortunately, however, the table also shows very wide variations prevalent, while the original test sheets indicate a considerable number of bars falling short of the requirements. The breaking load averages, as given in the table, are based on individual loads duly corrected for variations in cross-section dimensions from standard.

TABLE I.—SUMMARY OF TRANSVERSE TESTS.

2 by 1-in. Standard Pipe Test Bars. Supports 24 in. apart

Set No.	Number of Sound Bars	Average Breaking Load, lb.	Variation in Strength		Average Ultimate Deflection, in.	Variation in Deflection	
			Lb.	Per cent		In.	Per cent
1	14	2230	355	15.9	0.401	0.075	18.7
2	15	1913	485	25.3	0.382	0.147	38.5
3	13	1980	310	16.2	0.397	0.105	26.4
4	10	1996	240	12.0	0.326	0.055	16.9
5	9	2640	499	19.0	0.424	0.115	27.1
6	12	2128	350	15.5	0.355	0.072	20.4
7	11	2139	351	16.4	0.354	0.120	33.9
8	14	2275	325	14.3	0.398	0.087	21.9
9	13	2518	535	21.2	0.369	0.086	23.3
10	13	2325	330	14.2	0.378	0.075	20.0
11	13	2190	275	12.5	0.380	0.078	20.5
12	16	2274	455	20.0	0.358	0.100	35.8
13	15	2378	340	14.3	0.352	0.092	26.1
14	12	1955	151	7.7	0.311	0.033	9.7
15	4	2012	131	6.5	0.352	0.037	10.5
16	14	2550	351	13.8	0.323	0.088	27.2
17	6	2637	127	4.8	0.341	0.028	8.2
18	12	2705	214	7.9	0.338	0.052	15.4
19	8	2611	420	16.1	0.338	0.106	31.6
20	8	1859	267	14.3	0.320	0.069	21.5
21	11	1965	250	12.7	0.391	0.097	24.9
22	8	2377	148	6.2	0.361	0.042	11.7
23	9	2424	194	8.0	0.323	0.047	14.5
24	8	1892	167	8.8	0.329	0.058	17.6
25	13	2131	255	11.9	0.340	0.046	13.5
26	13	2063	260	12.6	0.338	0.066	19.5
Total	294	....	....	....	.....	.....	....
Average	...	2236	292	13.4	0.360	0.076	21.4

Of the 26 sets of bars with a total of 377 bars, 294 of these were sound, or 78 per cent. The greatest variation in the breaking strength of any set was 535 lb., the least variation 127 lb., or 25.3 per cent and 4.8 per cent respectively. The greatest variation in deflection of any set was 0.147 in., and the least was 0.028 in., or 38.5 per cent and 8.2 per cent respectively.

Respecting the ability of the test bars in these tests to pass the 0.30-in. deflection requirement at 2000 lb. and at 1900 lb., the following data were taken from the individual curves and test sheets:

Of the 294 good 2 by 1-in. standard pipe test bars,

255, or 80.0 per cent, passed the requirement of breaking with a minimum load of 2000 lb.

84, or 28.6 per cent only, however, passed the combined requirements of minima of 2000 lb. and 0.30 in. at rupture.

270, or 91.8 per cent passed the requirement of breaking with a minimum load of 1900 lb.

93, or 31.6 per cent only, however, passed the combined suggested requirements of minima of 1900 lb. and 0.30 in. at rupture.

As there was some suggestion of a compromise on minima of 1900 lb. with 0.25-in. deflection, this was looked into, and it was found that 151, or 51.3 per cent of the bars, had passed this.

This still left the question of a proportionate increase in deflection over 0.30 in. when the breaking load would go above the 2000 lb. required, and above the 1900 lb. suggested. This proportionate increase was to be preferably 0.030 in. for every 200 lb. increase in load, but was modified to 0.025 in. for every additional 200 lb. The individual test tables were next examined along this line, and elaborate tables showing the following items worked out: Breaking load, deflection at 1900 lb., final deflection, all corrected to bars of 2 by 1-in. standard; then columns for what the final deflection would have been had an increase of 0.025 in. for every 200 lb. been put on the deflection observed at 1900 lb., and similarly, had this increase been 0.030 in. per 200 lb. The object of these two calculations was to see whether the actual final corrected end result in deflection was larger than the proposed requirements, or not. It might be stated parenthetically, that the engineers welcomed a greater deflection than the proposed requirement, as this would indicate elasticity on the part of the pipe made. It was gratifying to note in the results obtained that in every case that 0.30 in. deflection was obtained at 1900 lb. as also at 2000 lb., the actual deflection increment was always greater than that of the proposed requirement, and that, therefore, there was no need to burden a proposed set of specifications with a required deflection increase per 200 lb. additional load above either 2000 or 1900 lb. as might eventually be decided upon. The actual deflection increment was not only greater than the proposed

0.025 in. per 200 lb. load increase, but also greater than the 0.030-in. increment originally desired.

Fig. 1, from which the portion of the curves from zero to 1000 lb. have been omitted to save space, shows a broken line based upon the proposed deflection and load requirements of 0.30 in. at 1900 lb., minima. This means a deflection increment rate of 0.0315 in. per 200 lb. load. This line, when continued at the same slope beyond the 1900-lb. loadpoint, shows that all the test sets attaining the 1900-lb., 0.30-in. basis, gave better deflection values than the 0.0315-in. rate, as also the originally proposed 0.030-in. rate; and much better deflection results than the proposed 0.025-in. increment rate.

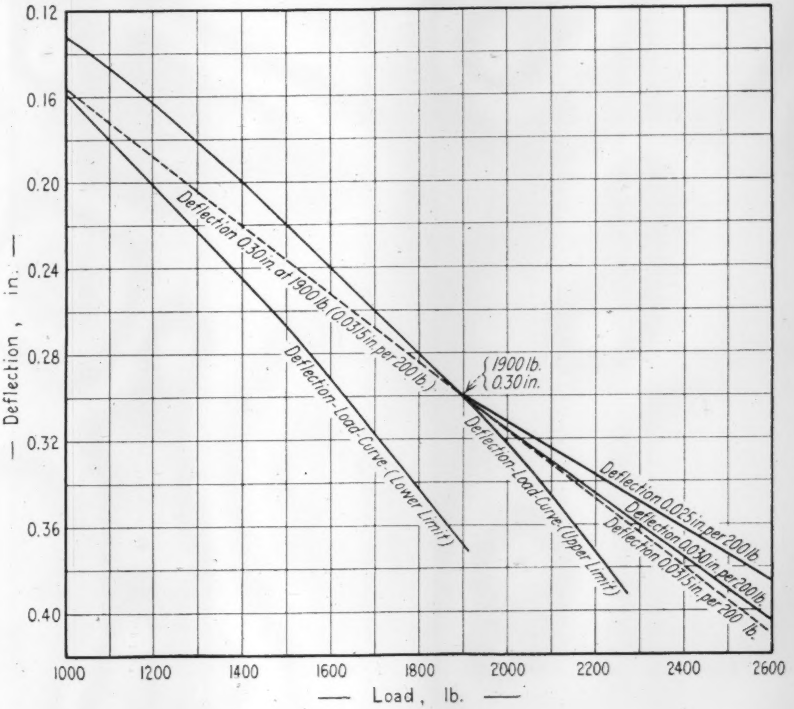

FIG. 1.—Relation of 2 by 1-in. Test Bars Passing 1900-lb. Load Point with 0.30 in. Deflection to Proposed Deflection-Load Increment Requirement.

The off-hand conclusion to be derived from a scrutiny of Table I is that the key-point involved in changing from the present test requirements for cast iron going into pipe to more rigid ones, lies in fixing a minimum deflection at a definite load point instead of at the point of rupture.

Tests of A.S.T.M. Arbitration Test Bars.—In Table II are given the analyses and physical tests of the A.S.T.M. standard arbitration bars. In each of the sets, arranged according to the silicon content, the analyses are averages of three samples, selected as previously explained. Similarly, the values of tensile strength are the averages of three tests. The transverse tests were made on a total of 289 bars, and with the deflections give a fairly complete picture of the arbitration bar as applied to cast iron for pipe. The table has been arranged to give the silicon content of the several sets of bars in three groups: namely, the low range (1.50 per cent silicon), for heavy pipe; the medium weight range (1.75 per cent silicon); and the light varieties (2.00 per cent silicon). These three groups have been averaged in Table III (*a*).

TABLE II.—ANALYSES AND PHYSICAL TESTS OF A.S.T.M. ARBITRATION TEST BARS.

Sets arranged in order of increasing silicon content.
Each chemical analysis is average of three samples.
Arbitration Bar 1¼ in. in diameter, tested on supports 12 in. apart. Total number of tests, 289.
Tensile strength determined on standard specimens for cast iron, taken from broken Arbitration Bars. Each value average of three tests.

Set No.	Chemical Composition, per cent							Tensile Strength, lb. per sq. in.	Transverse Test	
	Si	S	Mn	P	Combined Carbon	Graphitic Carbon	Total Carbon		Breaking Load, lb.	Ultimate Deflection, in.
	LOW SILICON									
5	1.45	0.094	0.48	0.53	0.77	2.75	3.52	25 450	3 405	0.094
13	1.45	0.110	0.42	0.64	0.72	2.78	3.50	22 830	3 418	0.103
16	1.47	0.063	0.95	0.86	0.93	2.58	3.51	31 370	3 577	0.096
11	1.48	0.114	0.40	0.75	0.70	2.90	3.60	26 030	3 008	0.104
10	1.51	0.114	0.46	0.65	0.82	2.73	3.55	26 680	3 499	0.105
19	1.53	0.097	0.48	0.65	0.92	2.51	3.43	32 150	3 675	0.104
9	1.55	0.117	0.30	0.72	0.93	2.40	3.33	26 400	3 312	0.099
22	1.60	0.091	0.66	0.80	0.84	2.73	3.57	26 820	3 496	0.106
1	1.66	0.127	0.40	0.55	0.69	2.78	3.47	27 160	3 368	0.105
	MEDIUM SILICON									
8	1.70	0.097	0.42	0.58	0.76	2.89	3.65	25 760	3 031	0.106
23	1.72	0.096	0.35	0.70	0.88	2.45	3.33	29 760	3 676	0.103
18	1.73	0.079	0.62	0.75	0.82	2.55	3.37	35 370	3 917	0.101
6	1.74	0.091	0.39	0.74	0.79	2.86	3.65	23 220	2 818	0.089
25	1.75	0.089	0.66	0.59	0.82	2.78	3.60	22 800	3 220	0.100
26	1.75	0.082	0.67	0.69	0.95	2.63	3.58	21 070	2 958	0.098
21	1.77	0.094	0.47	0.66	0.68	2.94	3.62	22 200	2 873	0.098
24	1.80	0.078	0.46	0.62	0.82	2.93	3.75	21 800	2 865	0.095
12	1.82	0.110	0.36	0.65	0.68	2.84	3.52	24 900	3 186	0.089
14	1.85	0.087	0.37	0.79	0.79	2.78	3.57	24 130	2 960	0.102
4	1.86	0.084	0.50	0.73	0.60	2.97	3.57	23 800	2 699	0.082
17	1.87	0.085	0.42	0.75	0.68	2.67	3.35	32 515	3 554	0.100
	HIGH SILICON									
7	1.95	0.059	0.54	0.76	0.74	2.97	3.71	23 200	2 863	0.084
20	2.00	0.078	0.41	0.69	0.89	2.82	3.71	20 580	2 702	0.088
3	2.08	0.065	0.67	0.78	0.56	3.20	3.82	24 610	3 037	0.107
15	2.09	0.074	0.35	0.82	0.71	2.85	3.56	23 550	2 910	0.098
2	2.10	0.082	0.47	0.48	0.81	2.79	3.60	22 150	3 018	0.107

As the arbitration bar is unquestionably too short to give deflection results of value to the cast-iron pipe industry, it is, therefore, beside the point to give full data on this part of the investigation here. However, as of general interest, the following summary of the average results of the several test bar sets is given, to correspond with a similar summary of the regular 2 by 1-in. pipe test bars:

NO. OF SETS	NO. OF BARS	AVERAGE TRANSVERSE STRENGTH, LB.	VARIATION IN TRANSVERSE STRENGTH,		AVERAGE DEFLECTION IN.	VARIATION IN DEFLECTION,	
			LB.	PER CENT		IN.	PER CENT
26	289	3265	513	16.0	0.100	0.025	25.0

NOTE.—289 good bars of a total of 397, or 73.0 per cent.

The grand average of the above A.S.T.M. bars of 3265 lb., with 0.10-in. deflection, would be considered as representing very good iron. The standard specifications for light iron castings call for a minimum breaking load of 2500 lb. with 0.10-in. deflection, or much less than the above record.

Referring again to Table III (*a*) as corresponding to 1.50, 1.75 and 2.00 per cent silicon, it will be noticed that the tensile and transverse strengths drop off regularly as the silicon increases, and that the deflection becomes lower as the bars are weaker. The particular study of the A.S.T.M. test bars, while not of direct value in the study of the proposed specification changes, nevertheless is highly interesting as bearing on the subject of predicting the strength of cast iron from its composition. This the writer has always held is not possible specifically, though capable of approximation. The elaborate data available gave an opportunity to test the matter out, and a series of tabulations was worked out to cover the point. The importance of the subject may be best understood when noting the constant attempts to regulate strength and composition jointly by specification.

The silicon effect has already been given, and runs normal. The next element to consider, as most affected by the silicon, is the total carbon. The series of tests would fall into three groups: namely, 3.25, 3.50 and 3.75 per cent, allowing a range of 12.5 per cent either way. These are given in Table III (*b*). The general experience is followed out, namely, that for the same silicon content, the lower the total carbon, the higher the strength. Again, for the same total carbon, the lower the silicon the higher the strength. The bad exception is the 3.25-per-cent total carbon and low-silicon combination, which runs the wrong way.

The next point involved is the condition of the carbon in the castings, as affected by the silicon and other factors. While any analysis of cast iron for graphite and combined carbon is true only for the spot from which the sample was taken, yet samples taken under the A.S.T.M. requirements give the average of the entire cross-section of the piece, and hence are fairly comparable. The series of tests were therefore worked out on the silicon-graphite basis, as shown in Table III (*c*). The principles that would govern in this case are: the higher the graphite, for equal silicon percentages, the weaker the metal; and the lower the silicon, for equal graphite, the stronger the metal. The general trend is in these directions, but the variations are large. A similar tabulation for 0.60, 0.75, and 0.90 per cent combined carbon, for the three ranges of silicon, also gave proper tendencies but erratic figures. Finally, for the carbon-

TABLE III.—AVERAGE OF VALUES FROM ARBITRATION TEST BARS REPORTED IN TABLE II, CLASSIFIED IN VARIOUS WAYS.

Classification	Silicon, per cent	Number of Bars	Average Tensile Strength, lb. per sq. in.	Average Transverse Breaking Load, lb.	Average Ultimate Deflection, in.
(*a*) CLASSIFIED ACCORDING TO SILICON					
SECTION					
Heavy	1.50	89	27 510	3 426	0.102
Medium	1.75	146	26 940	3 290	0.100
Light	2.00	54	22 970	2 917	0.097
(*b*) CLASSIFIED ACCORDING TO TOTAL CARBON					
TOTAL CARBON, PER CENT					
3.25	1.50	9	26 400	3 312	0.099
	1.75	42	33 350	3 774	0.101
	2.00	..	.....	.....	....
3.50	1.50	80	27 635	3 812	0.113
	1.75	67	24 820	3 207	0.102
	2.00	24	22 910	2 959	0.098
3.75	1.50	..	.....	.....	....
	1.75	37	23 500	2 891	0.096
	2.00	30	23 020	2 884	0.093
(*c*) CLASSIFIED ACCORDING TO GRAPHITIC CARBON					
GRAPHITIC CARBON, PER CENT					
2.50	1.50	33	32 560	3 537	0.096
	1.75	28	33 760	3 884	0.102
	2.00	..	.....	....	....
2.75	1.50	46	25 850	3 436	0.093
	1.75	78	25 550	3 323	0.103
	2.00	32	22 330	2 895	0.099
3.00	1.50	10	26 030	3 008	0.104
	1.75	45	23 320	2 863	0.095
	2.00	22	23 900	2 950	0.095

silicon relation, a table was constructed giving the silicon relation to a combined carbon-graphite ratio. The results here were not at all satisfactory, running in the wrong direction about as much as in the right. With silicon-sulfur relations but little could be done, the classification for sulfur being: below 0.05, between 0.05 and 0.08, and above 0.08 per cent. Manganese and phosphorus were not variable enough to affect the influence of the silicon and carbon content.

On the whole, it was observable that while in the individual foundry it was possible to meet even small fluctuations in strength and deflection by suitable chemical changes day by day, the changes required for similar fluctuations in the physical properties of the iron as cast into bars in each of the other foundries might be somewhat different. The base analysis of the iron in a given class of pipe in one shop would vary somewhat from the base analysis of the iron in the same class of pipe in another shop. All of which shows the futility of specifying analysis with physical properties, unless the limits in variation are made rather wide.

The question arises in what respects the results in Northern pipe foundries would differ from those of the South. To see what, if any, differences there are, the following ranges in analyses, strength and deflection data are given:

RANGE OF ANALYSES:	NORTHERN FOUNDRIES	SOUTHERN FOUNDRIES
Silicon, per cent..........	1.45 – 2.10	1.47 – 2.09
Sulfur, "	0.059 – 0.127	0.063 – 0.097
Manganese, "	0.30 – 0.67	0.35 – 0.86
Phosphorus, "	0.48 – 0.78	0.59 – 0.76
Total Carbon, "	3.33 – 3.82	3.38 – 3.75
RANGE OF STRENGTH AND DEFLECTION:		
Tensile Strength, lb per sq. in..	22 150 – 27 160	20 580 – 32 515
Transverse Breaking Load, lb..	2 699 – 3 499	2 702 – 3 917
Deflection, in................	0.082 – 0.107	0.088 – 0.106

This would seem to indicate that there is not very much difference in the behavior of the two classes of irons, so far as making pipe is concerned.

GENERAL DISCUSSION OF TEST DATA

In working for a long time with the standard 2 by 1-in. test bar for cast-iron pipe, it is but natural that the applicability of this bar for the class of castings in question should also be studied. In looking over the standards for thickness of pipe it will be noticed that progressively for each pipe size there is an increasing thickness of section; further, that this thickness increases relatively for the same size of pipe as the duty becomes heavier, pipe of a given size passing successively from Class A to B, and then to C and finally into the heaviest, or Class D. Thus, there is a steady progression of increased section thickness in two directions, from 0.42 in. for a 4-in. pipe of Class A, to a 60-in. Class D pipe with a thickness of 2.38 in. The foundryman has to adjust his mixtures to cover these varying section thicknesses, as indicated by the three silicon ranges selected for these tests. Experience has shown that for this wide range of pipe thickness, from 0.42 up to 2.38 in., a range of silicon from 2.00 down to 1.25 per cent is necessary. Yet the metal going into all this product is judged by a bar of one section only, and this bar will show quite a different structure for the extremes in composition necessary in making pipe. And yet this bar must pass under one set of load and

TABLE IV.—CHEMICAL COMPOSITION STRENGTH AND DEFLECTION OF 2 BY 1-IN. STANDARD PIPE TEST BARS (SEE TABLE I).

Sets arranged in order of increasing silicon content. Compare with Table II.

Set No.	Number of Bars	Chemical Composition, per cent					Breaking Load, lb.	Ultimate Deflection, in.
		Si.	S.	Mn.	P.	Total Carbon		
				LOW SILICON				
5	9	1.45	0.094	0.48	0.53	3.52	2 640	0.424
13	15	1.45	0.110	0.42	0.64	3.50	2 378	0.352
16	14	1.47	0.063	0.95	0.86	3.51	2 550	0.323
11	13	1.48	0.114	0.40	0.75	3.60	2 190	0.380
10	13	1.51	0.114	0.46	0.65	3.55	2 326	0.378
19	8	1.53	0.097	0.48	0.65	3.43	2 611	0.338
9	13	1.55	0.117	0.30	0.72	3.33	2 518	0.369
22	8	1.60	0.091	0.66	0.80	3.57	2 377	0.361
1	14	1.66	0.127	0.40	0.55	3.47	2 230	0.401
				MEDIUM SILICON				
8	14	1.70	0.097	0.42	0.58	3.65	2 275	0.398
23	9	1.72	0.096	0.35	0.70	3.33	2 424	0.323
18	12	1.73	0.079	0.62	0.75	3.37	2 705	0.338
6	12	1.74	0.091	0.39	0.74	3.65	2 128	0.353
25	13	1.75	0.089	0.66	0.59	3.60	2 131	0.340
26	13	1.75	0.082	0.67	0.69	3.58	2 063	0.238
21	11	1.77	0.094	0.47	0.66	3.62	1 965	0.391
24	8	1.80	0.078	0.46	0.62	3.75	1 892	0.329
12	16	1.82	0.110	0.36	0.65	3.52	2 274	0.358
14	12	1.85	0.087	0.37	0.79	3.57	1 953	0.340
4	10	1.86	0.084	0.50	0.73	3.57	1 996	0.326
17	6	1.87	0.085	0.42	0.75	3.35	2 637	0.341
				HIGH SILICON				
7	11	1.95	0.059	0.54	0.76	3.71	2 139	0.354
20	8	2.00	0.078	0.41	0.69	3.71	1 859	0.320
3	13	2.08	0.065	0.67	0.78	3.82	1 907	0.396
15	4	2.09	0.074	0.35	0.82	3.56	2 012	0.352
2	15	2.10	0.082	0.47	0.48	3.60	1 913	0.382

deflection minima. Theoretically, there should be a test bar of the same thickness as the pipe made—a manifestly impracticable procedure—and different strength and deflection minima as well. Or with a single bar, the strength and deflection minima should be adjusted to cover classified ranges of pipe thickness. As it is to-day, the engineers demand that the test bar shall show a moderate-strength but elastic iron, and the foundryman strives to give them such test bars. Whether, however, the pipe made from irons that give such test bars are really what the engineers think they are, may be quite another matter. None the less, until there is cooperation in research along this line it is useless to change the present standard of testing. The argument just given, however, shows how much is yet ahead of the two interested parties.

To show the actual situation as observed in the tests on 2 by 1-in. bars, Table IV has been prepared. It shows only in a very general way the drop in strength and deflection as the silicon goes up progressively. The variations are too great to make them exceptions that prove the rule. It will be observed, however, that the lower range of silicon gave metal which passed the specifications easily, so far as the average results are concerned. The medium range of silicon already showed trouble from the middle up, and the higher range in silicon gave results which averaged unsatisfactorily, showing, however, how difficult it was for the manufacturers to get soft enough iron for thin pipe, while risking rejections under the specifications. Some of the variation is, of course, due to irregularities in the charging and melting practice at the several foundries, and also to the scrap that has to be used to close up the crystallin structure of the metal. This tends to vitiate the finer distinctions that should be apparent in the strength results for the rather wide range in the principal element affecting the carbon condition, namely, the silicon. The strength curves obtained showed this irregularity rather forcibly, for it did not seem to matter very much whether the silicon was high or low, the result was pretty nearly the same, which explains why a single bar has so far served the industry sufficiently well to be reasonably satisfactory. And this brings the subject matter to the discussion of the curves obtained under test.

STUDIES RELATING TO KIND OF TEST BAR

First about the 2 by 1-in. pipe test bar itself. This is a traditional bar which seems to have been evolved in the cast-iron pipe industry. It has the advantage of being long and hence good for showing elasticity, and it approximates the shape of the metal in the pipe itself. It has the disadvantage of having a cross-section with four corners of metal harder than the rest. The effect of this condition is shown in every individual test curve, in that there is a drop in the curve toward the end of the test which is quite characteristic of the bar. In some instances, with the harder bars, when this part of the test was reached there was heard a distinct snap in the metal showing that the outer fibers of the two lower corners had parted. To get more light on this point, a number of 2 by 1-in. bars were made of three mixtures, hard, medium and soft, just like the regular ones, in dry-sand molds in a vertical position, with top pour. Each of these bars were sliced on a planer into three strips of equal width. These latter bars were thus $\frac{2}{3}$ by 1 in. in cross-section, and were tested transversely on a 24-in. span with the 1-in. side vertical. The tests are summarized in Table V (*a*). It will be noted that the comparatively harder corner pieces of the standard test bars were stronger than the softer centers, as was to be expected; and that the softer center strips had a considerably greater deflection for the medium and higher silicons than the corresponding harder corner pieces. As these comparatively narrow strips made rather slender test pieces when broken on supports 24 in. apart, the broken halves were again subjected to the same test on supports 12 in. apart, to give a safer judgment on the transverse strength of the iron, the deflection of the long pieces being trustworthy enough. These tests are summarized in Table V (*b*). The results corroborate those of the first series, and emphasize the disadvantage of the rectangular bar as against a round one. Incidentally, it may be stated that in

TABLE V.—TESTS OF BARS $\frac{2}{3}$ BY 1-IN. IN CROSS-SECTION, CUT FROM 2 BY 1-IN. STANDARD PIPE TEST BARS.

All bars were tested with the 1-in. side vertical.

Silicon, per cent	Breaking Load, lb.		Ultimate Deflection, in.		Grain Structure
	Corner Bars	Center Bars	Corner Bars	Center Bars	
(*a*) TESTED ON 24-IN. SPAN					
1.56	481	469	0.335	0.336	Fine
1.83	583	515	0.354	0.436	Medium
2.20	496	454	0.350	0.400	Coarse
(*b*) TESTED ON 12-IN. SPAN					
1.56	1 029	929	0.091	0.106	Fine
1.83	1 123	1 050	0.095	0.114	Medium
2.20	1 089	1 014	0.082	0.112	Coarse

Great Britain, where the 2 by 1-in. bar is also used for testing purposes, it is placed upon the supports 24 in. apart, but on edge—that is with the 2-in. dimension for depth, and the 1-in. side for width, whereas we here test these bars laid flat.

The change in curvature on the part of the test curves is an interesting one, and occurs around a load point of about 1500 lb.

When the test curves were summarized and the composite curve for each set of test bars was plotted on section paper, it was noticed that the arbitration bar tests were all bunched up at the top of the sheet, and that while the curves were sufficiently sensitive to differences in breaking loads, the deflection results which averaged 0.1 in. for the entire lot, or one-third the amount of the 2 by 1-in. bars broken on supports 24 in. apart, were too variable in the individual sets of bars themselves to be of any value. The regular 2 by 1-in. bars, on the other hand, are entirely too scattered about, both for load and deflection, to allow the drawing of deductions as to limits against insufficiently elastic, as also against weak irons. Moreover, the marked change in curvature due to the previously mentioned hard corners is disconcerting, and leaves the mind unsatisfied as to the reliability of this bar inasmuch as the strength of these corners must needs be seriously affected by slight differences in metal temperature, composition and mold surface conditions.

TABLE VI.—TRANSVERSE TESTS OF BARS SUGGESTED AS PREFERABLE TO THE 2 BY 1-IN. AND ARBITRATION TEST BARS.

Number of Bars	Chemical Composition, per cent			Average Breaking Load, in. (Corrected) lb.	Average Ultimate Deflection, in.	Grain Structure
	Si	S	Mn			
(*a*) PROPOSED INTERNATIONAL ARBITRATION BAR FOR EXPORT. 1.20 IN. IN DIAMETER. BROKEN ON SUPPORTS 18 IN. APART						
18	1.44	0.082	0.54	1 846	0.198	Fine
18	1.81	0.099	0.47	1 694	0.205	Medium
16	2.19	0.096	0.43	1 930	0.216	Coarse
(*b*) TEST BAR $1\frac{3}{8}$-IN. IN DIAMETER. BROKEN ON SUPPORTS 18 IN. APART						
9	1.56	0.099	0.57	2 442	0.156	
14	1.88	0.071	0.66	2 308	0.190	
12	2.24	0.093	0.59	2 312	0.167	

With the feeling that neither the present flat pipe test bar nor the standard arbitration bar are competent when judging the quality of the metal entering this peculiar class of castings, the question arose as to what bar would do. The natural solution would seem to lie in the selection of a bar that was round instead of rectangular in section, as shown by the good load characterization of the arbitration bars. The distance between supports in the tests, however, would require shortening from the 24 in. now used for the pipe bar, to enhance the reliability of the deflection results, and lengthening were the arbitration bar used, to increase the sensitiveness in regard to deflections. As this viewpoint is covered by the proposed "International Arbitration Bar for Export," which is 1.2 in. in diameter, broken on supports 18 in. apart, and would mean only the lengthening of the present arbitration bar correspondingly, a set of tests was made of such a bar under conditions of silicon content to approximate light, medium and heavy pipe. Table VI (*a*) gives the summaries of the three sets made. The resulting curves obtained from these tests indicate that for a nice

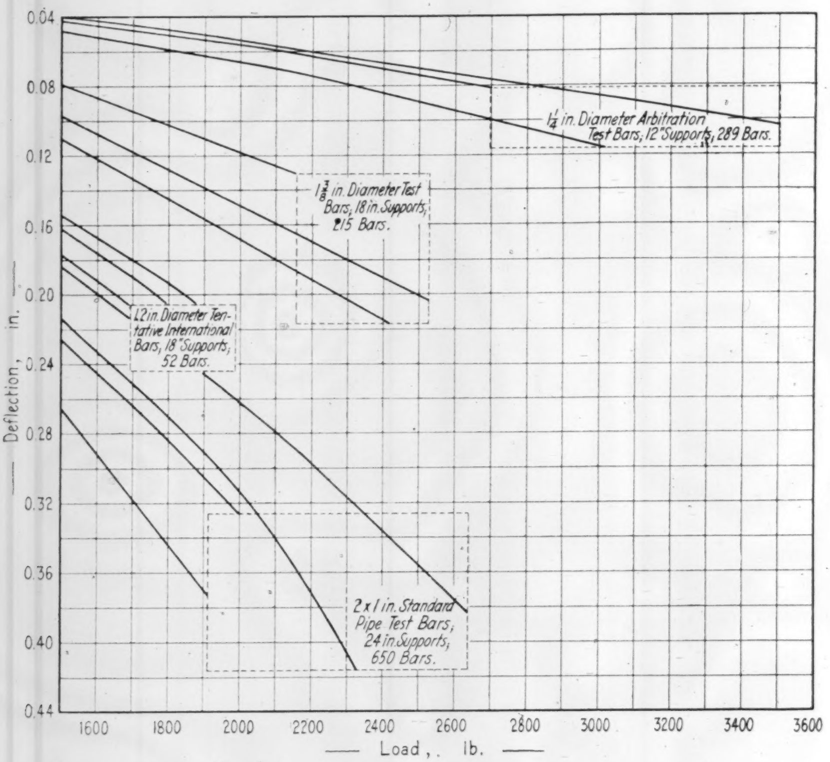

FIG. 2.—Comparative Curve Ranges for Various Cast-Iron Test Bars.

balance between sensitiveness to load and to deflection, not much of an improvement had been obtained over the 2 by 1-in. bars tested on supports 24 in. apart. To get this balance the bar should be somewhat thicker and give a smaller range of deflections. A series of bars was next made with a diameter of $1\frac{3}{8}$ in., and broken on supports 18 in. apart. The results from these bars are given in Table VI (*b*). The curves obtained from these tests fall about midway between those from the pipe test bars and the arbitration bar, and looked about equally sensitive to load and to deflection. Moreover, the relation of transverse to tensile strength of the iron in a bar of this diameter is just that for the pipe test bar, and while it is incorrect to consider this relation to be 1 to 10, the $1\frac{3}{8}$-in. bar is no worse in this respect than the 2 by 1-in. bar.

Fig. 2 shows the comparative curve ranges for the several classes of test bars discussed. Only the outer curves are given, the balance falling within the rectangles of load-deflection results shown.

As a consequence of this set of tests, the writer recommended to the engineers and the manufacturers of the Joint Committee, that tests with this $1\frac{3}{8}$-in. bar be conducted side by side with the regular pipe test bar for a period of six months, to see whether this apparently satisfactory measure of load and deflection would hold out, and also to secure a mass of results for the further study of the test bar question for cast-iron pipe. While the manufacturers of cast-iron pipe were willing to try the matter out for a sufficient time to allow judgment thereon, and one large Southern pipe maker actually carried on a line of such tests for a considerable period for his information, the engineers did not take kindly to the idea of a change in test bar and so the matter went by. None the less, the question of relation of diameter of bar to length under transverse test will have to be studied sooner or later, and no better way can be devised than to study the individual curves in their relation to each other and taken in connection with the composition of the metal, its pouring temperature, mold conditions and possible subsequent heat treatment.

The anomaly of having but one limit for strength and but one for deflection in the case of the standard pipe test bar, when metal going into the bar must have compositions suited to different thicknesses of pipe and hence widely varying, has previously been mentioned. That is, metals of different character intended, when cast into different sections, to bring out the same qualities in each, are nevertheless not cast into test bars of thickness proportional to the respective sections, but into a bar of the same thickness for all sections; and we depend upon observations of this one bar for a check upon the quality of metals of different characteristics. This is a very inexact procedure, and the very purpose of the consumer to be certain of what he gets is entirely lost. Since a variety of test bar thicknesses is out of question, from a practical point of view, what we should do is to specify different strength requirements for the single test bar so that the necessary differences in metal composition are taken into account. An iron going into heavy pipe must be comparatively low in silicon, and consequently gives a very strong test bar which will not bend very far; yet the pipe made of this low-silicon iron is practically as resilient as a lighter pipe of a small diameter for which a higher silicon mixture has to be taken, and which gives a weaker test bar with greater deflection. The use of one bar is unquestionably the correct procedure for simplicity and uniformity in practice; hence any necessary distinction must be made through different strength and deflection requirements in this bar. With one set of requirements only for the standard bar, the minima for strength and deflection must be made low enough to care for both hard and soft irons, as has just been indicated. What, therefore, becomes a very strict requirement in the one case, is a very loose one for the other.

TABLE VII.—PERCENTAGE OF GOOD BARS AT 1900-LB. LOAD, PASSING VARIOUS DEFLECTION LIMITS.

Number of Bars Passing Deflection Limit Indicated	Deflection Limit at 1900-lb. Load in.	Percentage of 294 Good Bars Passing Indicated Deflection
93	0.30	31.6
122	0.29	41.5
143	0.28	48.6
157	0.27	53.4
185	0.26	62.9
202	0.25	68.7
224	0.24	76.2
235	0.23	80.0
247	0.22	84.0
257	0.21	87.4
260	0.20	88.4

Table VII shows in detail just how the twenty-six different sets of test bars, made from irons of the wide compositions as shown in previous tables, have passed or failed to pass the several deflection minima at the 1900-lb. load point. The serious part of the problem, however, is indicated by the fact that of the twenty-six sets of bars made and tested, eleven sets failed entirely to pass the 1900-lb. point with 0.30-in. deflection at that point; and but one set out of the lot passed completely. It may be stated in this connection that the sets which failed in the above requirement were those with low and low to medium silicon, the bars being fairly strong, but not bending sufficiently by the time the 1900-lb. load was reached.

TESTS OF BARS FROM SPECIAL MIXTURES OF PIG AND SCRAP

The natural inference to be made from the above discussion would seem to be to establish more than one set of minima in place of a single set. Indeed, the manufacturers of pipe offered to agree to requirements of 2000-lb. minimum breaking load with 0.25-in. deflection at the 2000-lb. load point, for the standard test bar representing the iron going into the heavy classes of pipe; and 1900-lb. minimum breaking load with 0.28-in. deflection at the 1900-lb. load point for the standard test bar representing the iron going into the lighter classes of pipe. This, however, was not considered by the engineers to be a sufficient strengthening of the old specification requirements, and after considerable discussion it was decided to see if it might not be possible to improve the quality of the metal going into pipe, as shown by the standard pipe test bar, by making better quality mixtures. The manufacturers promptly authorized the writer to undertake this investigation, and it was carried out with the following underlying thought: In planning a series of tests to give the information desired, there had to be kept in mind the limitations imposed by commercial considerations. Necessarily, charcoal and nickel-chrome pig irons had to be barred, for the higher grade metal realized would be too costly for cast-iron pipe. Again, a much stronger pipe could be made with steel scrap additions to the mixture, but two things would follow: The breaking strength would go much higher in proportion to the rise in deflection, and the considerable chances for oxidation and sand difficulties would mean much bad pipe and a consequent rise in cost. The breaking strength of pipe is considered high enough at the present time; what is desired is to increase the deflection. Hence, steel scrap as a specific improvement could not be considered. As to melting processes, furnace and electric melting would mean much higher tonnage costs. So it was finally decided to make use of the regular sources of pig and scrap now available, but to test the efficacy of pig-scrap mixtures of different proportions. To minimize the uncertainty of "bought" scrap compositions, this was limited, for the series, to 30 per cent, 20 per cent, 10 per cent and none with 10 per cent of the whole added in each case in the shape of the sprues and scrap pipe of the establishment. Thus the mixtures became the following: Pig-Scrap, 60–40, 70–30, 80–20 and 90–10.

Metallurgically, melting stock in the gray-iron foundry can be divided into two classes: "New" iron, namely, pig iron, or metal which had not gone through the oxidizing influences of cupola or furnace melting; and "remelted" stock, which is again divided into the sprues or "home" scrap, and "bought" or "foreign" scrap. The composition and history of "home" scrap is known; the bought scrap is an unknown quantity.

Where it is desired to get at relative effects of different proportions of pig and scrap, it is common foundry knowledge that the first melt does not usually show satisfactory results, and only when the remelt has been used repeatedly will results be normal for that particular mixture. That is to say, it seems as if the "sprues" or scrap from the previous day's melt acquire the characteristics of the new mixture arrangement more and more as the melts progress. Hence, for these tests, each mixture was twice repeated giving three separate sets of bars. Care was taken that the pig iron and scrap were uniform, large quantities of molten metal being actually pigged to supply the "sprues" used to the extent of 10 per cent in every mixture.

TABLE VIII.—ANALYSES OF TEST BARS FROM SPECIAL MIXTURES CONTAINING VARIOUS PROPORTIONS OF PIG AND SCRAP.

Class of Pipe	Percentage of Pig Iron	Chemical Composition, per cent.				
		Si	S	Mn	P	Total Carbon
Heavy (Si = 1.50)........	60	1.57	0.114	0.45	0.59	3.64
	70	1.57	0.103	0.47	0.57	3.59
	80	1.52	0.106	0.48	0.53	3.60
	90	1.44	0.097	0.50	0.56	3.68
Medium (Si = 1.75)........	60	1.79	0.090	0.53	0.72	3.65
	70	1.79	0.106	0.45	0.76	3.56
	80	1.72	0.089	0.47	0.72	3.60
	90	1.71	0.074	0.54	0.71	3.62
Light (Si = 2.00)........	60	2.10	0.089	0.59	0.77	3.43
	70	2.07	0.095	0.55	0.71	3.35
	80	2.12	0.094	0.59	0.82	3.35
	90	1.93	0.095	0.52	0.78	3.35

At least six molds for the 2 by 1-in. test bar, and the same number for the suggested $1\frac{3}{8}$-in. bar, were poured each time, all from the same ladle en route to the pipe molds of the shop. In order to get approximately the same physical properties for the iron put into the three classes or weights of pipe, it was necessary to vary the analyses accordingly. Hence 1.50 per cent silicon was selected for heavy, 1.75 per cent silicon for medium and 2.00 per cent silicon for light pipe mixtures. The actual analyses came out very close to these requirements, as will be seen in Table VIII. It will be of interest to state that the large ladles of molten metal from which these test bars were made were actually poured into the following work: 1.50-per-cent silicon metal was run into 30-in. Class "B" water pipe; 1.75-per-cent silicon metal was run into 20-in. gas pipe; and 2.00-per-cent silicon metal was run into 6-in. Class "B" water pipe.

The average transverse strengths and deflections of the several pig-scrap mixtures made are given in Table IX. Only the values for the second remelt (the third heat) of each mixture is given, as most reliable in showing what was sought after. The results from all the bars, however, are used in the final summary given later on. Test results for both the standard pipe test bar and the suggested $1\frac{3}{8}$-in. diameter bar are given. An inspection of this table shows that if the bars had been a little stronger, more of them would have passed the present-day specifications. In any case the deflections were very good. The purpose of the tests being to show whether it was possible to improve the quality of the metal by changes of pig-scrap proportions, it will be noticed that a slight improvement is manifest in strength, and certainly in deflection, when more pig iron is used in the mixtures. This is shown even a little better by the results with the round bar than by those with the rectangular bar. That better pipe is produced when the pig-iron percentages used are high is a well-known fact, and before war-time conditions demoralized the iron industry but

TABLE IX.—TRANSVERSE TEST RESULTS ON BARS FROM SPECIAL MIXTURES CONTAINING VARIOUS PROPORTIONS OF PIG AND SCRAP.

For chemical compositions, see Table VIII.
Values reported are for third run only of each mixture.

Approximate Silicon Content, per cent	Percentage of Pig Iron	2 by 1-in. Test Bars, Tested on 24-in. Span			$1\frac{3}{8}$-in. Diameter Test Bars, Tested on 18-in. Span		
		Number of Bars	Average Breaking Load, lb.	Average Ultimate Deflection, in.	Number of Bars	Average Breaking Load, lb.	Average Ultimate Deflection, in.
1.50	60	5	1 910	0.319	7	2 376	0.159
	70	5	1 878	0.320	6	2 359	0.161
	80	5	1 863	0.393	4	2 222	0.159
	90	6	1 894	0.362	4	2 394	0.178
1.75	60	5	1 828	0.309	4	2 263	0.150
	70	5	2 040	0.337	7	2 312	0.154
	80	5	1 887	0.300	7	2 348	0.142
	90	5	1 878	0.326	7	2 366	0.160
2.00	60	6	1 910	0.306	7	2 224	0.149
	70	7	1 907	0.322	5	2 348	0.142
	80	6	1 872	0.380	6	2 366	0.160
	90	6	2 025	0.382	7	2 383	0.189
Average for all Silicon Contents	60	16	1 900	0.311	18	2 292	0.153
	70	17	1 938	0.326	18	2 360	0.162
	80	16	1 868	0.359	17	2 236	0.180
	90	16	1 939	0.360	18	2 380	0.175

little scrap went into this class of castings. The iron industry, however, has not yet returned to normal operation, if by that is meant a return to conditions just before the war. Throughout the foundry industry, scrap percentages in mixtures have remained high and are likely to continue that way, even growing larger where the new desulfurizing method by chemical means is resorted to. Furthermore, furnaces for foundry pig iron are to-day run with proportionally less coke and more cast-scrap burdens than before the war, so that even where pipe plants are favorably located with respect to their pig iron supply, this is not of as good a quality as was formerly the case, and is not likely to become better again with labor costs as they are.

ANALYSIS OF ALL TEST DATA WITH RESPECT TO SPECIFICATION REQUIREMENTS

Since this investigation resulted in no tangible solution for the problem of improving the quality of metal going into pipe in a practicable way, the manufacturers of cast-iron pipe deemed it advisable to study further the proposal of fixing a minimum deflection at a given load point, and what it might mean to their daily practice if set at, lower, or higher than the 1900-lb. load point with 0.30-in. deflection minimum under discussion. The author was accordingly instructed to analyze further all the test results up to this time and calculate from the test curves made of each bar just what percentage of the bars made would have passed had a minimum of 0.30-in. deflection been demanded at an 1800, 1900 and 2000-lb. load point, respectively. This proved an unusually laborious task, for though the results had all been duly corrected for variations in dimensions from standard, a majority of the test pieces were 0.01 in. or more over or under size and it was necessary now to locate corrected positions for the three designated load points and get the corresponding deflections.

A study of the very elaborate series of tables prepared in this analysis gave some interesting figures on the actual load-deflection situation. First, to find out just how many bars had passed the several load points selected, the following data were compiled:

	NUMBER	PER CENT PASSING
Total number of sound bars tested	650	..
Bars passing 1800-lb. load point	614	94
" " 1900-lb. " "	516	79
" " 2000-lb. " "	376	58

This would indicate that, apart from the deflection involved, the 1800-lb. strength is easily attained; the 1900-lb. strength is reached by almost 80 per cent of the bars; but the 2000-lb. strength—or that of the present specifications—was not attained to an extent giving anything like satisfaction. To analyze the figures in question a little further, to learn if a differentiation existed between the bars from heavy and light-pipe mixtures, the following comparison was made:

	HEAVY-PIPE IRON (SI = 1.50)		LIGHT-PIPE IRON (SI = 2.00)	
	NUMBER	PER CENT PASSING	NUMBER	PER CENT PASSING
Total number of sound bars involved..	230	..	173	..
Bars passing 1800-lb. load point	218	95	153	88
" " 1900-lb. " "	190	83	122	70
" " 2000-lb. " "	154	67	59	34

Here, again, the passing percentage for the 1800-lb. point was excellent, that for 1900 lb. was good for the heavy-pipe iron and not so good for the light, while for the 2000-lb. point two-thirds of the heavy-pipe iron passed but only one-third got by for the light-pipe iron—another indication that a differentiation in requirements for the quality of the metal, as shown in the standard test bar, should be made between at least heavy and light sections of the pipe this metal is poured into.

In the foregoing data, however, the deflections have not been considered. This point is included in Table X, in which is given the number of test bars passing the 1800, 1900, and 2000-lb. load points, respectively, with the deflection points to correspond given in successive stages of 0.005-in. increment. (For simplicity, only that portion of the rather long table of deflection-load results is given which lies between the deflection limits of 0.215 and 0.319 in. The actual range runs between 0.170 and 0.440 in.) Thus, 17 bars of the entire 650 sound bars tested had a deflection of 0.250 to 0.254 in. at a load point of 1800 lb., 19 bars had a deflection within these limits at 1900 lb., and 17 bars had a deflection within these limits at 2000 lb.; while 342 bars passed the 1800-lb. point, 328 bars reached the 1900-lb. point, and 292 reached 2000 lb., all with a deflection of 0.250 in. or more.

The purpose of the table was to determine, from the comprehensive tests made, just what deflection it would be fair to ask of the cast-iron pipe industry under any of the three minimum load points considered. Naturally, the question of what would be fair to ask of the cast-iron pipe industry is based upon what the industry is able to do under the conditions of the present period, and how the manufacturers look upon it on their side as against the viewpoint of the purchasers and their engineer representatives. These viewpoints might be very much opposed to each other and still have no bearing upon the status of this paper. None the less, if an agreement as to the percentage of test bars that could reasonably be expected to pass under existing practice were reached, the above table would serve as the determining factor in setting the deflection minimum for a given load point, for the tests represent the daily practice of eight of the best operated pipe foundries of America.

Suppose it were agreed upon that 75 per cent of all the bars made should be considered as good work, then 75 per cent of 650 bars would mean that 487 constituted the passing point of the table. An examination of the table shows that 0.22 in. would be the minimum deflection possible of attainment under existing practice, whether the load point be taken at 1800 or 1900 lb. The 2000-lb. point is out of question, as but 57 per cent of the bars reached this deflection at that load point. On the other hand, if it were agreed that only the very best of the cast-iron pipe now made should be subject to specification, then the proposed stiffening up of the specification requirements to 0.30-in. deflection at 1900-lb. load would mean that only 26 per cent of the test bars made in this investigation would have passed. That this is possible is shown by the very figures, but as it would mean the rejec-

TABLE X.—DEFLECTIONS OF 650 SOUND BARS (THE ENTIRE TEST SERIES) AT SELECTED LOAD POINTS.

Deflection, in.	At 1800-lb. Load			At 1900-lb. Load			At 2000-lb. Load		
	Number of Bars Having Deflections within the Limits Indicated	Bars with Deflection Equal to or greater than Lower Limit of Range Indicated		Number of Bars Having Deflections within the Limits Indicated	Bars with Deflection Equal to or greater than Lower Limit of Range Indicated		Number of Bars Having Deflections within the Limits Indicated	Bars with Deflection Equal to or greater than Lower Limit of Range Indicated	
		Number	Per cent		Number	Per cent		Number	Per cent
0.215—0.219, incl.	34	508	78	15	495	76	3	374	58
0.220—0.224, "	30	474	73	21	480	74	3	371	57
0.225—0.229, "	23	444	68	21	459	71	11	368	57
0.230—0.234, "	14	421	65	22	438	67	11	357	55
0.235—0.239, "	22	407	63	34	416	64	17	346	53
0.240—0.244, "	17	385	59	22	382	59	19	329	51
0.245—0.249, "	26	368	57	32	360	55	18	310	48
0.250—0.254, "	17	342	53	19	328	51	17	292	45
0.255—0.259, '	17	325	50	14	309	47	24	275	42
0.260—0.264, "	14	308	47	22	295	45	25	251	39
0.265—0.269, '	23	294	45	19	273	42	14	223	34
0.270—0.274, '	24	271	42	12	254	39	21	209	32
0.275—0.279, "	26	247	38	11	242	37	10	188	29
0.280—0.284, "	24	221	34	10	231	35	16	176	27
0.285—0.289, "	26	197	30	12	215	33	9	162	25
0.290—0.294, "	16	171	26	22	203	31	7	153	24
0.295—0.299, "	23	158	24	12	181	28	9	146	22
0.300—0.304, "	20	132	20	29	169	26	6	137	21
0.305—0.309, "	12	112	17	17	140	22	11	131	20
0.310—0.314, "	13	100	15	17	123	19	10	120	18
0.315—0.319, "	6	87	13	9	106	16	14	110	17

tion of three-fourths of the output of a great industry, which would have to find channels other than specification orders, prices would climb very promptly because of the higher grade and hence costlier materials that would have to be used.

It is well at this juncture to consider the cast-iron pipe as a casting. It is a long cyclinder of uniform thickness for its length, except at the immediate ends. It is always poured with the mold in vertical position, and with "top pour"—the ideal method for cast iron as the temperature of the metal is the same at every point of the mold when in first contact with it. Cooling progressing upward successively, the top metal solidifies last, and hence feeding is ideal. From the nature of the casting, the mold, and the way it is poured, a pipe will have the outer and inner walls or surfaces reasonably sound if mold and core have been well dried. The interior metal, between inner and outer wall surfaces, however, may be good or bad, fairly sound or full of shrinks, gas pockets and dirt, depending upon the quality of the metal used in the mixtures, and the correctness of the melting procedure. Without going specially into the chemical side of the question and discussing the deleterious effect of high sulfur and phosphorus, and particularly the oxidation effects observable with poor melting practice, it is the interior metal and its physical structure which begins to tell when corrosion has proceeded beyond the sound outer and inner shells of the pipe. Hence the importance of using good materials as a basis and giving these materials properly carried out conversion processes to put them into serviceable pipe.

CONCLUSION AND RECOMMENDATION

It seems to be indicated from this study that two points need future attention. The engineers should aid the manufacturers with information on what physical requirements cast-iron pipe should fulfill, and should help shape the necessary tests to cover the situation. The manufacturers, on the other hand, should cooperate in this study and in addition observe the trend of future development in the industry and shape their plant equipment and extension accordingly. Hence, the writer has recommended to the Joint Committee of Engineers and Manufacturers that the former form an Advisory Committee to cooperate with the manufacturers as a Joint Research Association, the engineers to give particular attention to developing satisfactory tests for cast-iron pipe, both on the pipe itself and the material entering into it, while the manufacturers work toward standardization of their materials and methods of operation, and extend this work over a sufficient period of time to enable them to modify their plants where necessary without undue hardship.

DISCUSSION ON CAST IRON FOR PIPE

Mr. Barbour. MR. F. A. BARBOUR.[1]—I have been interested in this subject for a good many years, as a member of the committees of the American and New England Water Works Associations. In 1916, these committees, acting jointly, issued a so-called tentative specification, which was submitted to the manufacturers, and which, among other things, called for a relation between breaking load and deflection. As originally proposed, the standard 2 by 1-in. bar, with 24-in. span was required to show a breaking load of not less than 2000 lb. and a deflection of not less than 0.32 in. with an increase in deflection of not less than 0.03 in. for each 200 lb. of breaking load in excess of 2000 lb. Subsequently, these requirements were modified to a minimum breaking load of 1900 lb., a deflection for bars breaking at this load of not less than 0.30 in. and an increment of 0.025 in. for each 200 lb. of breaking load above 1900 lb. In other words, if a bar breaks at 1900 lb., the deflection shall not be less than 0.30 in.; at 2100 lb., not less than 0.325 in.; at 2300 lb., not less than 0.35 in., and so on up.

Right here I want to call Mr. Moldenke's attention to what I believe is a misinterpretation in his work of the relation between breaking load and deflection, as proposed by the water associations' committees. It was not our intention that there should be a deflection of 0.30 in. at 1900 lb. if the bar did not break at 1900 lb. What we proposed was that, if the bar broke at 1900 lb., there should be a deflection of not less than 0.30 in.; if it went on up, the deflection at the point of breaking should be 0.30 in. plus the specified increment of 0.025 in. for each 200 lb. of load in excess of 1900 lb. Thus, deflection at the breaking point shall equal $0.30 + \frac{(\text{breaking load} - 1900 \text{ lb.})}{8000}$. Instead of this, Mr. Moldenke—as I understand his paper—has observed the deflection at 1900 lb., whether the bar broke or not, and if at that point it did not show 0.30 in. deflection, it was condemned. As the increment found by Mr. Moldenke with increasing load is greater than 0.025 in. it follows that some of the bars which he has interpreted as failing to meet the requirements may have developed a deflection at the point of breaking equal to 0.30 in. plus 0.025 in. for each 200 lb. in excess of 1900 lb.

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[1] Consulting Hydraulic and Sanitary Engineer, Boston, Mass.

Mr. Barbour.

As to the viewpoint of the engineer, interested in water supply, as to the revision of standard specifications, in the first place, it should be noted that a great many of the bars broken by Mr. Moldenke would condemn the iron tested even under the present specifications and without regard to any relation between breaking load and deflection. In other words, these tests show that present-day irons have not the strength and relative deflection of the metal which has been obtainable under the old specifications for many years.

Mr. Moldenke's conclusion is that, under existing conditions, it is impossible to get an iron that will meet the proposed relation between breaking load and deflection, and he therefore suggests that the specified requirements should be amended so as to fit the material obtainable. An equally justified deduction from his tests is that the results constitute an indictment of present methods of making pipe—not so much of the pig used, perhaps, but of foundry practices, overworking of cupolas, oxidation, etc. We, as engineers using water pipe, think that in developing new specifications, we ought to require at least as good iron as was obtainable twenty years ago and because the present metal, as tested, fails to meet the proposed test bar requirements, and also fails in great measure to meet the requirements of the old specifications, does not demonstrate that the proposed relation between breaking load and deflection is infeasible. The manufacturers can meet the specification suggested by the Water Works Associations, and if I had an order of several thousand tons to place to-morrow morning I would have no difficulty in obtaining bids on the specified basis of breaking load and relative deflection. Mr. Brush of the New York Water Supply has for some years used the test bar specifications proposed by the Water Works Associations in 1916 and is not having any difficulty in obtaining pipe.

Of course the tentative draft of specifications included a number of revisions other than those in reference to test bars. It suggested certain chemical limits, which Mr. Moldenke in his report to the foundrymen rather frowned on—despite the fact that chemical requirements are included in the specifications for car wheels and other types of castings. Mr. Moldenke, however, did say in his report that a maximum limit should be set for the sulfur content, making this $\frac{1}{12}$ of 1 per cent instead of $\frac{1}{10}$ of 1 per cent, as proposed by the Water Works Associations.

Another most important revision of these specifications is that in reference to the pipe coating. Some of us believe that the vicarious bar is a pretty poor test of the metal in the pipe and one only to be continued because of its simplicity, but as to the need of an improved

Mr. Barbour. coating, there can be no question in the mind of anyone. To-day, an engineer, estimating the necessary size of pipe, figures on a carrying capacity of about two-thirds of that of new pipe, to allow for the roughening of the interior surface by use. Economically, therefore, the most important thing in the whole problem of revised specifications, is the development of a suitable coating, and I am sure that the Water Works Associations will welcome this new committee of the American Engineering Standards Committee, particularly, if by its taking up the problem a better coating can be made available. I believe that the cooperation of the American Society for Testing Materials, with the opportunity of utilizing the results of the studies made by the Committee on Waterproofing offers a chance for substantial progress.

Mr. Wiggin. MR. T. H. WIGGIN.[1]—Mr. Barbour has expressed a good many views of the water works fraternity to which I belong, but I have a few other things that I might say. Some 28 years ago in connection with the inspection of cast-iron pipe for the Metropolitan Water Works of Massachusetts, I made a lot of transverse tests[2] on 2 by 1-in. bars flatwise on 24-in. span. From these tests I drew a number of conclusions which are very similar to some now presented by Mr. Moldenke. After having drawn some of these conclusions I found in an old volume (1849) of a British Commission that they also had reached the same conclusions so that the subject seems to be pretty well covered by conclusions.

The main thing that always impressed me in the testing of cast iron is the difference to which Mr. Moldenke calls attention, namely, that the interior of a casting is different from the outside and that this same iron poured in a thin casting is so different in texture from the iron when poured in a thick casting as not to be recognizable as the same material. As a matter of fact, it is not the same material: the constituents occur partly in different allotropic forms or combinations so that they produce an entirely different physical result.

This knowledge led me to question whether the vicarious test bar, as Mr. Barbour calls it, is of any use. I made a schedule at that time of different sizes of bars for different thicknesses of pipe. For example, I proposed to test pipe under 0.5 in. in thickness with a bar 0.6 in. thick and 2 in. wide, because I found that the test bar cools a a little faster than the pipe and therefore it requires a slightly greater thickness in order to give it the same texture. I undertook to match

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[1] Consulting Engineer, New York City.

[2] For a very complete description of these tests, which were the first on 2 by 1-in. bars for pipes, see T. H. Wiggin, "The Manufacture and Inspection of Cast-Iron Pipe," *Journal of Engineering Societies* (1899).

Mr. Wiggin.

textures, assuming that, if the textures matched, the physical properties would be approximately alike. In the same way I suggested a 2 by 1-in. bar for pipe between 0.5 and 0.9 in. in thickness and bars 3 by 1.5 in. for pipe from 0.9 to 1.4 in. in thickness.

About 15 years later, in the work of the New York Water Supply I used test bars 3 by 1.5 in. in acceptance tests for the iron in flexible-jointed pipe that were cast for the Narrows sub-marine crossing between Brooklyn and Staten Island. I thought better knowledge was obtained from these bars than could have been obtained from 1 by 2-in. bars for such heavy pipe ($1\frac{5}{8}$ in. in thickness). It was at first necessary to make some experiments with the larger bars because they did not give quite the proportionate strength as compared with 2 by 1-in. bars.

Now the English, as Mr. Moldenke has stated, use that very system and it seems to be as logical as any system could be for an indirect or vicarious test. The French system of cutting a piece out of the casting itself and testing it is in line with the French characteristics of accuracy and logic. That kind of a test is much more pleasing to me than a test of a test bar although I am sure that I could go to one or two adjacent foundries, as I did in those earlier days, and by spending all my time could tell with the aid of test bars and inspection what was happening in the production of the iron. I am equally sure that no inspector who does not pay attention to metallurgy can do it.

A 2 by 1-in. test bar taken alone does not show much of anything. I found that, when tested flatwise transversely on a 24-in. span, these bars might have a strength of 1900 lb. and a deflection of 0.30 in. and prove to be entirely suitable, in fact excellent, iron for small castings and at the same time be very poor iron for big castings. In one foundry that I attended daily, the proprietor was bound to have the best and nothing but the best of iron in his pipes, and he apparently used the same expensive, soft grades both in the small 4-in. and 6-in. castings and in the 48-in. pipes, many of which were 1.4-in. thick. That iron when cast in the big pipes had something of the appearance of coal. An inspector's hammer could be driven deeply into it though the iron in the 2 by 1-in. test bar was sufficiently close. The large pipes, as a matter of fact, gave good enough service although there was some evidence of their being less strong than pipes made with cheaper iron and some scrap, which were supplied by another foundry where they had a chemist who understood the difference between iron for thick castings and iron for thin castings.

The idea of using a single bar and varying the strength and

Mr. Wiggin. deflection in accordance with the thickness of casting has something in its favor if one could watch the foundry processes, but I have known exceptions which were disturbing. For example, I have seen iron that would test about 1900 lb. and 0.30-in. deflection, and in the natural order of events would have been perfectly suitable iron for small castings but it was not at all suitable for any casting. It had a sort of unhealthy look; it was a close-grained iron, and when put into small castings it was mottled. If one had been guided by the test bars alone and not by inspection, bad iron would have been accepted and this is not infrequently the case, particularly where much mixed scrap is used.

Another method of testing, akin to that used by the French, is that of cutting a sample from the pipe and my thoughts have been going in that direction for some time past. When the De la Vaud centrifugal pipes were first brought to the fore, the question came up as to how to test them. For some reason, even the proponents of the vicarious test bar did not advocate it here, though the difference between pipe and bar as compared with that in the case of sand-cast pipes is only one of degree. Mr. Barbour, I believe, is responsible for the idea of cutting a ring 1 in. wide from the end of the centrifugal pipe and testing the ring, by deforming it to the point of fracture, between the heads of a compression testing machine.

In a few tests which I witnessed it was found that rings cut from centrifugal pipe which had been annealed gave about twice the strength and half the deflection of sand-cast pipe of equal thickness. These are corrected figures, taking account of the fact that the sand-cast pipes were thicker than the centrifugal pipes.

Carrying this idea one step further, why is not the ring test the best test for the ordinary pipe? It was found in some tests that were made through the kindness of one of the foundries that the ring test had no greater precision than any other method of testing. In the early days of 2 by 1-in. test bars I had a considerable number of bars cast as twins, many of them with a little connecting gate so that they had the same iron, the same temperature and almost the same instant of pouring. Yet, they gave differences in strength as high as 440 lb. in 2000 lb. and the average difference of the whole series of 85 pairs was about 100 lb. The same thing is true apparently of these rings. In other words, pipes are no more uniform in strength than are test bars, due to the accidental variations. I say this with a little mental reservation. No pipe is of exactly equal thickness on the two sides. When two rings are cut off, one may be tested in a little different position from the other. The property of a ring when deformed is

Mr. Wiggin.

that it will be more influenced by the thickness under points of contact than it will be by the remainder of it. Therefore, to test the precision properly, the ring should be cut into sections and each section tested with the ends on rollers. This is practically the way a ring from a big pipe would be tested to avoid the necessity of a large testing machine. A ring that was divided would furnish several test specimens and give a measure of precision of the test.

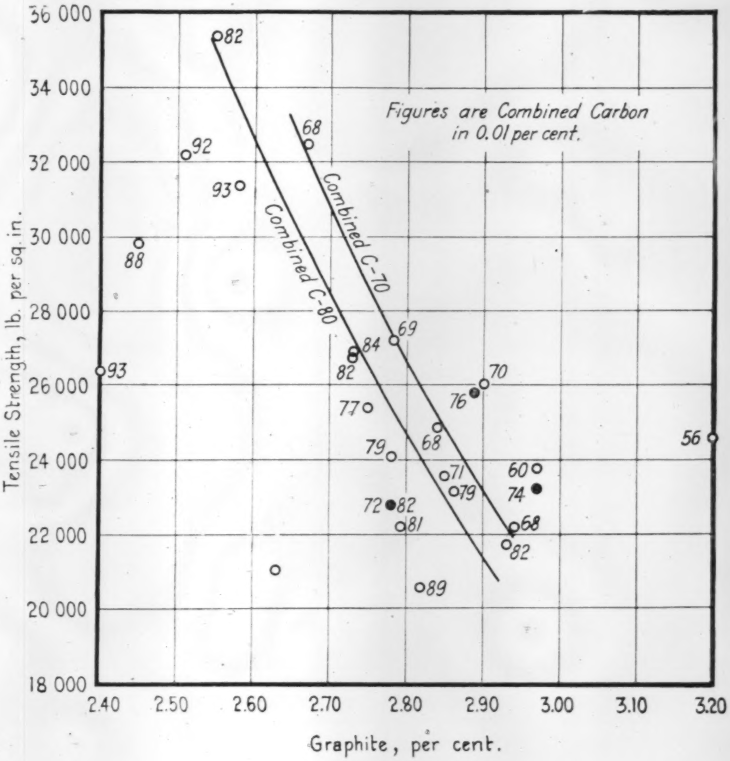

FIG. 1.

The ring test cannot yet be offered as a panacea by any means, but I think it is a very promising line of investigation, and I hope it will be pursued by the coming sectional committee on pipes to be organized under the auspices of the A.E.S.C.

Mr. Schwartz.

MR. H. A. SCHWARTZ[1] *(by letter)*.—It was pointed out many years ago by Howe that even the gray cast irons should be considered as steels modified in properties by the mechanical interruptions produced in the metallic matrix by the graphite crystals. We should,

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[1] Manager of Research, National Malleable and Steel Castings Co., Cleveland, Ohio.

Mr. Schwartz. accordingly, be able to explain the tension test data in Mr. Moldenke's Table II from the chemical data in the same table, by considering the effect upon the properties of the matrix of the several elements present, alloyed with iron, and of the free graphite as a mechanical interruption.

The effect of graphite is obviously the prime determining factor. Were there not the question of its geometric distribution, we could draw the conclusion, as in malleable cast iron, that its harmful effect was directly related to its amount. The matrix may in all those cases be expected to consist of pearlite and either ferrite or cementite. Having in mind the silicon contents here involved, it is hardly likely that any of the alloys except Set 3 and Set 4 should be hypoeutectoid. We have, therefore, to consider a hypereutectoid steel interrupted by graphite. Hypereutectoid steels grow weaker with increasing carbon content, that is, with increased cementite. We should thus expect that Mr. Moldenke's material should grow weaker the higher the combined carbon and the higher the free carbon.

In the accompanying Fig. 1, his table has been translated into graphic form by plotting graphite content for each alloy as abscissa and its tensile strength as ordinate. Beside each point has been written its combined carbon content.

Two lines have been drawn showing the relation of strength to graphite for a combined carbon of about 0.70 and 0.80 per cent, respectively.

In only three cases, marked by solid circles, is there any radical departure of the points from their expected location.

The points with 0.90 per cent and over, of combined carbon, are found in the right portion of the field, but erratically located, doubtless because of the embrittling effect of considerable quantities of free cementite. It is thus shown that we need not consider the elements silicon, manganese, phosphorus, and sulfur in accounting for the physical properties of these irons, although it is, of course, obvious that the distribution of carbon between graphite and cementite is an expression of its chemical composition in regard to some or all of these elements.

Mr. Moldenke's carefully collected data agree as well as could possibly be expected with the theory, having in mind the difficulties encountered in the sampling and testing of gray cast iron.

Mr. Moldenke. MR. RICHARD MOLDENKE (*Author's closure by letter*).—I am very glad indeed to have the definite statement of Mr. Barbour regarding what the engineers really intended in the load and deflection requirement in their proposed changes in the standard specifications. The fact that a bar breaking at 1900 lb. should have at least 0.30-in. deflection, and if breaking at higher loads should show a regular

Mr. Moldenke. increment of 0.025 in. per 200 lb. was understood by the manufacturers of cast-iron pipe, but that a bar breaking at any point above 1900 lb. could have a deflection below 0.30 in. at a load of 1900 lb., provided it came up to the formula:

$$\text{Deflection} = 0.30\text{ in.} + \frac{(\text{Breaking Load} - 1900\text{ lb.})}{8000}$$

was not grasped as intended. In fact, inquiry among the producing members of the Joint Committee of Engineers and Manufacturers indicates the understanding that in any case when the bar reached a load of 1900 lb. a minimum of 0.30 in. was to be required. All the studies on the elaborate series of tests were made with this in view. Perhaps the formal sessions of the Joint Committee precluded that informal discussion so necessary to get at the individual viewpoints with exactness.

The results of the tests naturally take a different aspect when calculated on the above formula. A table by 100-lb. variations in breaking load would be as follows:

Whatever deflection there may be at 1900 lb., the end deflection of
Bars breaking at 1900 lb. must be 0.300 in.
" " " 2000 " " " 0.312 "
" " " 2100 " " " 0.325 "
" " " 2200 " " " 0.337 "
" " " 2300 " " " 0.350 "
" " " 2400 " " " 0.362 "
" " " 2500 " " " 0.375 "

As promised at the annual meeting, I have gone over the tables of results and have applied the engineers' formula to 483 of the individual tests, and take pleasure in giving the following summaries:

FIRST SERIES OF TESTS: MADE IN 4 NORTHERN AND 4 SOUTHERN FOUNDRIES

Silicon, per cent	Number of Bars	Average Breaking Load, lb.	Average End Deflection, in.	Average Required End Deflection by Engineers' Formula, in.	Number of Bars Passing Engineers' Formula Requirements	Number of Bars Passing 1900-lb. Requirement	Average Deflection at 1900 lb., in.	Number of Bars Passing 0.30-in. Deflection at 1900-lb. Load
1.50	107	2 408	0.357	0.356	57	107	0.258	12
1.75	136	2 195	0.340	0.325	86	127	0.283	33
2.00	51	1 803	0.366	0.312	33	36	0.341	29
Totals and Av.	294	2 232	0.351	0.322	176	270	0.281	94
SECOND SERIES OF TESTS MADE IN ONE NORTHERN FOUNDRY								
1.50	64	1 876	0.325	0.317	27	28	0.332	26
1.75	56	1 891	0.323	0.310	26	29	0.311	19
2.00	69	1 924	0.368	0.317	32	35	0.347	29
Totals and Av.	189	1 898	0.340	0.315	85	92	0.331	74
Grand Totals and Averages	483	2 101	0.347	1.327	261	362	0.294	168

Mr. Moldenke. An analysis of the grand totals and averages of these 483 test bars shows the following: 362 of them, or 75 per cent, have passed the 1900-lb. load point before breaking, the average breaking load of the 483 bars being 2101 lb., with an average end deflection of 0.347 in. The end deflections actually required under the proposed Engineers' Formula would have meant an average of 0.327. This is substantially below the average found, though of the 483 bars only 261, or 54 per cent, would have passed the proposed requirements. The 362 bars passing the 1900-lb. load point before breaking, had an average deflection of 0.294 in. at that point; that is, they were under the 0.30-in. requirement originally understood to be necessary to pass. The number of bars passing the 1900-lb. load with 0.3-in. deflection at that point is only 168 out of the 483, or 34.8 per cent. Under Mr. Barbour's explanation of the real intent of the Engineers' proposed specification changes, the low figure of 34.8 per cent of the bars passing would, therefore, be raised to 54.0 per cent—which is gratifying, though still far below what an industry should be capable of accomplishing under specifications adapted to the factors that must be reckoned with in making cast-iron pipe.

It might be well to quote those sets of test-bar results which failed completely in passing the proposed Engineers' Formula requirement and also failed to pass the original 1900-lb. load with 0.30-in. deflection minima:

NUMBER OF BARS	SILICON, PER CENT	AVERAGE BREAKING LOAD, LB.	AVERAGE END DEFLECTION, IN.	REQUIRED END DEFLECTION, ENGINEERS' FORMULA, IN.
14	1.50	2550	0.230	0.360
8	1.50	2611	0.340	0.366
9	1.75	2424	0.325	0.343
12	1.75	2705	0.338	0.400
6	1.75	2367	0.343	0.409

It will be observed that the above are rather strong bars, though of too low deflection values. Considering that the silicon is low, the thickness of the pipe made with these irons was probably greater than the test bars. Had these bars been cut from the pipe itself the metal would have been softer and more resilient, and possibly perfectly satisfactory if recalculated to test bar dimensions and results. The point to be brought out is merely that it is unfair to the iron to have one bar for three or more grades of pipe unless the test requirements of that bar are adjusted accordingly. On the other hand, as Mr. Barbour has stated, Mr. W. W. Brush, of the New York Metropolitan Water Works Commission has been able to get pipe under these proposed advanced specification requirements. This is perfectly possible, though how much pipe has to be rejected before the required quota is obtained forms another side to the story. The difficulty of this situation lies in the fact that the manufacturer bends his whole energy toward meeting the test bar requirements rather than making ideal pipe. With the very basis of test bar requirements fundamentally wrong, what else can he do? **Mr. Moldenke.**

In commenting upon the poor showing of the tests in question as a whole, Mr. Barbour touches on two crucial spots: the inferior quality of the pig irons of the present day, and the imperfections in plant operations on the part of the manufacturers. Both criticisms are abundantly justified. I have continually and consistently pointed out the growing inferiority of our American foundry pig irons as the furnace tonnages have been forced upward. Instead of being content with units running between 250 and 450 tons capacity—tonnages of individual furnaces now get close to the thousand-ton mark. Under such conditions, the conversion of the ore to iron sponge and this to molten iron cannot be accomplished with that degree of freedom from iron oxide, which is found in the slowly operated furnaces with lower blast temperatures. Now to this undesirable situation comes the present practice of charging heavy scrap iron percentages with the furnace burden to partially make up the losses every merchant foundry iron furnace is under to-day. The result is that while the sulfur content of the molten scrap is reduced by the lime of the furnace burden, the oxidized condition of the metal itself cannot be changed by the mere melting as the solid and unchanged scrap reaches the furnace melting zone. Simple melting of that scrap in the cupola and subsequent treatment in the ladle with soda-ash would have given pig iron just as good. The unfortunate part of this situation is that we will continue to see train loads of scrap enter the yards of the blast furnace plants, so long as scrap prices are low enough to make it worth while. The solution lies in a set of strict specifications for testing pig iron in such a way that scrap additions to the furnace burden are discouraged. Otherwise the outlook for good pig irons based alone upon their analysis is rather hopeless.

The second point as to poor plant practice is also very pertinent. Our pipe shops have grown with the country. Economic conditions have eliminated so many shops that but few pipe plants remain, and these are all very large. Fierce competition at times has militated against any but the smallest expenditures for expansion—not to speak of betterments. So the net result has been vastly increased tonnage production with inadequate melting facilities. Cupolas are often-

Mr. Moldenke. times forced and the already bad pig irons are damaged still further in the oxidizing melting methods the foundry must use. It is easy to urge the raising of prices, and the engineers for the purchasing interests themselves urge this to get pipe made from more costly pig irons and with better melting practice. Such things are, however, not done as the laws of business and economics go. Hence the desirability of research work deliberately intended to show up inferior metal and inferior practice, with the ultimate view of corrective specifications. But before even this constructive program is undertaken, it seems to me—as the result of the rather elaborate investigation in question—that the very basis of the whole idea of obtaining light on the quality of the metal going into cast-iron pipe should be corrected to conform with the laws governing the behavior of cast iron. Until this has been accomplished it seems so useless to argue about load and deflection results on bars that are not representative of the situation.

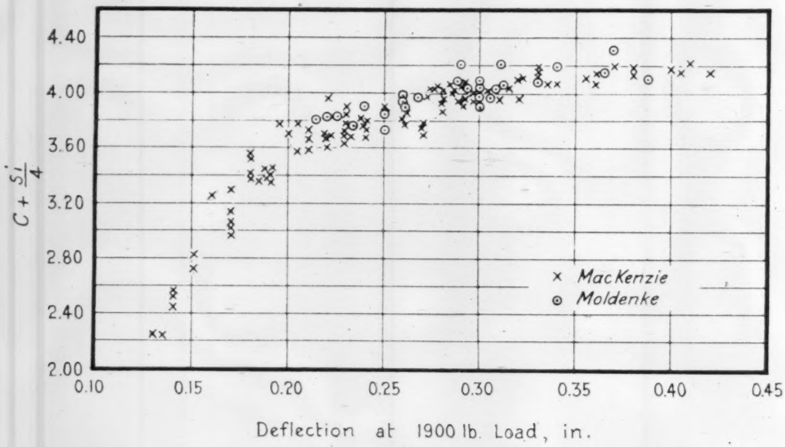

FIG. 2.—Relation Between $C + \frac{Si}{4}$ and Deflection at 1900 lb. Load.

Mr. MacKenzie. MR. J. T. MACKENZIE (*by letter*).—Thinking it would be interesting to compare the results of Mr. Moldenke with my own, I took the liberty of plotting his results for deflection at 1900 lb. on a chart showing the results of my bars at the same point. The sets shown are from his first investigation where he used only the standard pipe foundry mixtures, and are from practically every shop east of the Mississippi. The agreement seems to me to be quite remarkable. This chart is reproduced in the accompanying Fig. 2.

TYPES OF APPARATUS USED IN TESTING THE CORRODIBILITY OF METALS[1]

By Henry S. Rawdon,[2] A. I. Krynitsky[3] and W. H. Finkeldey[4]

Introduction

Any attempt to emphasize the importance of the study of the corrodibility of metals would seem uncalled for and superfluous. This problem is practically as old as that of the production of the metals themselves and its technical and vast economic importance is unquestioned. The widespread interest which is being manifested at present in the problem serves, however, to focus attention upon the methods for determining the relative corrodibility of various metals and the apparatus by which such tests can be readily carried out.

The American Society for Testing Materials is taking a very active part in the study of corrosion through its Committees A-5 and B-3, which deal with the corrosion of iron and steel and of non-ferrous metals, respectively. Although the forms of apparatus described below and, in one particular case, the test methods were developed independently in the laboratories with which the authors are associated, the committee activities serve to unite these separate endeavors, so that this paper may justly be considered as a joint contribution from the two corrosion committees of the Society.

This paper is limited to a description of the various types of apparatus used in studying the corrodibility of metals. The number of requests received for information of this kind, in the opinion of the authors, justifies the publication. Sufficient experimental results are not yet available, however, which will permit definite conclusions being drawn as to the relative merits of the different forms. A very considerable amount of work will be required before such definite recommendations can be made.

Types of Tests

The general character of all tests of the corrodibility of metals is, of necessity, determined by the nature of corrosion itself. A simple, satisfactory, and widely accepted definition of this term has not yet been advanced. Practically all are in agreement, however, that corrosion is a chemical process, whereas the deterioration of a metal by other means, for example, mechanical agencies, should be termed erosion. The two processes may and often do occur simultaneously on the same specimen, however. Tests for determining the corrodibility of metals should, then, be chemical in nature, and in planning the method of operation, one must take cognizance of the way the corrosive reagent shall be applied as well as the almost unavoidable accompanying accelerating influence of the surrounding atmosphere. The two most obvious methods for controlling the oxidizing effect of the atmosphere are either (*a*) to eliminate this variable entirely, or (*b*) to provide complete aëration so that the effect will be a maximum. In practice, the second method is, by far, the simpler one to carry out. For convenience in application, the corrosive medium is generally used as a liquid although in some cases a gaseous medium is preferable.

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[1] Published by permission of the Director of the U. S. Bureau of Standards.

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[4] New Jersey Zinc Co., Research Laboratory, Palmerton, Pa.

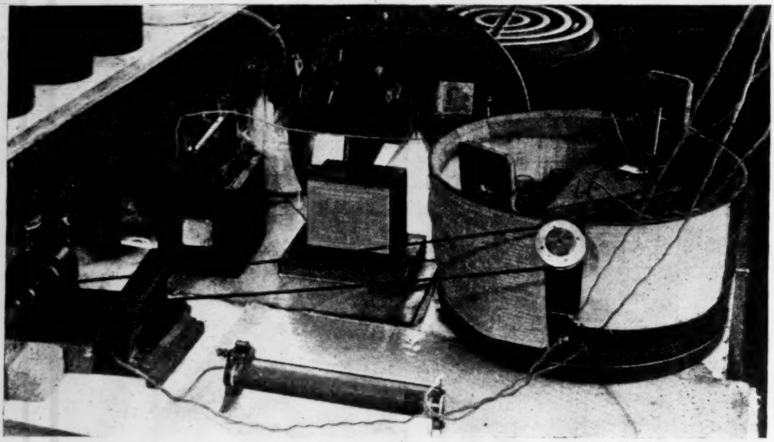
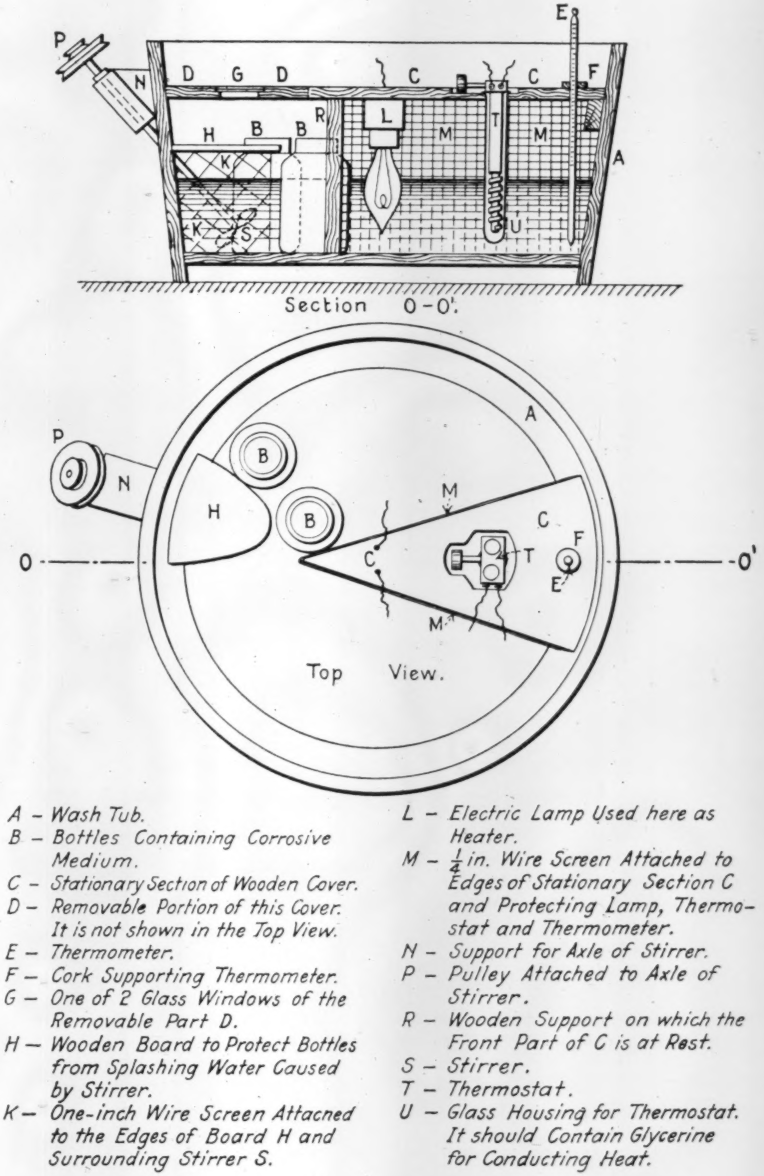


FIG. 1.—Apparatus for Conducting Corrosion Tests by Simple Immersion at Constant Temperature, used at Bureau of Standards.

The simplest method of testing is to immerse the specimen completely within the corrosive liquid either with or without precautions for agitating the liquid and for controlling the effect of atmospheric oxidation. The rate of attack of the specimen by the corrosive solution can usually be increased to almost any desired degree by making the specimen, while immersed within the liquid, the anode, and a piece of resistant metal such as platinum the cathode, completing the necessary electrical connections and applying suitable external electromotive force to the system. As an extension of the simple immer-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Top View.
A - Wash Tub.
B - Bottles Containing Corrosive Medium.
C - Stationary Section of Wooden Cover.
D - Removable Portion of this Cover. It is not shown in the Top View.
E - Thermometer.
F - Cork Supporting Thermometer.
G - One of 2 Glass Windows of the Removable Part D.
H - Wooden Board to Protect Bottles from Splashing Water Caused by Stirrer.
K - One-inch Wire Screen Attacned to the Edges of Board H and Surrounding Stirrer S.
L - Electric Lamp Used here as Heater.
M - $\frac{1}{4}$ in. Wire Screen Attached to Edges of Stationary Section C and Protecting Lamp, Thermostat and Thermometer.
N - Support for Axle of Stirrer.
P - Pulley Attached to Axle of Stirrer.
R - Wooden Support on which the Front Part of C is at Rest.
S - Stirrer.
T - Thermostat.
U - Glass Housing for Thermostat. It should Contain Glycerine for Conducting Heat.

FIG. 2.—Diagram of Sectional View of Apparatus of Fig. 1.

sion method, the specimen may be momentarily dipped into the liquid and then withdrawn into the air, the cycle being repeated indefinitely. A modification of this method, which perhaps approaches some types of service more closely than the preceding one, allows for a drying off of the specimen between successive immersions. In each of these two methods, the atmospheric oxygen is permitted to have its full effect. Any attempt to control or eliminate this variable would complicate the apparatus to such an extent as practically to eliminate it from most laboratories. The same is true also for the spray or mist corrosion test in which the specimens are confined within an enclosed space and the corrosive agent applied in the form of a cloud produced by "atomizing" it by means of compressed air.

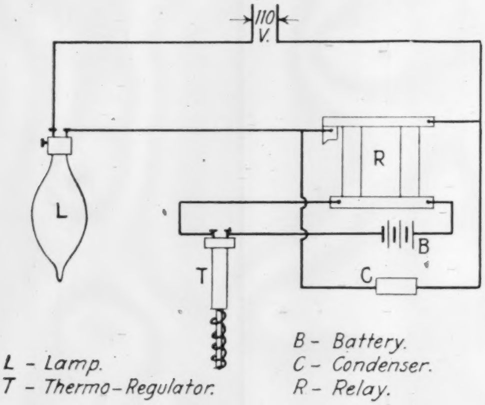


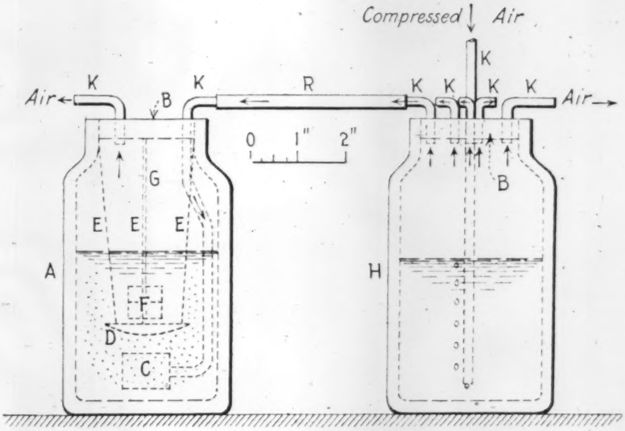
FIG. 3.—Arrangement for Controlling Temperature of Apparatus of Fig. 1.

For many materials, especially coated metals, a test method which simulates the conditions of atmospheric corrosion encountered in service is very desirable. These brief references to the various testing methods are amplified in the descriptions of the apparatus necessary for carrying them out given below.

APPARATUS

Simple Immersion.—Although corrosion tests of this kind are carried out more readily than the other kinds listed, the procedure is not quite so simple as the name might imply. The principal conditions which require control are those of temperature, agitation and aëration of the corroding solution. Possible change of concentration of the solution by evaporation must also be considered.

In Fig. 1 is shown a convenient set-up used for this test, the details of the apparatus being given in Fig. 2. The laundry tub which is used as the container is filled to the desired level with water which is heated by means of an incandescent bulb, and the temperature controlled by a thermostat (Fig. 3). The stirrer agitates the water vigorously so that its temperature is uniform. The bottles containing the corrosive liquid and the specimens under test are placed in the water and the outfit is covered, thus ensuring only slight changes in concentration of the solutions by evaporation.



A – One of 5 Bottles Forming a Unit.
B – Cork.
C – Porous Alundum Cylinder Hermetically Sealed at both Ends in such a Manner as to Permit Access to Compressed Air only.
D – Watch Glass Used here as Baffle Plate.
E – Threads by which D is Suspended. They are Attached to D by Means of Khotinsky Cement.
F – Specimen.
G – Thread to Suspend Specimen.
H – Bottle Distributing Compressed Air to 5 Bottles of the Unit. It should Contain Water or Corrosive Solution.
K – Glass Leads.
R – Rubber Connections.

FIG. 4.—Method of Aëration Used in Simple Immersion Corrosion Test.

If aëration of the solutions is desired, the set-up illustrated in Fig. 4 is used. This is inserted within the bath. The incoming air after being freed from carbon dioxide passes through the central bottle in which is contained either water or a solution similar to that used in the particular corrosion test under way. Thus the chances for changes of concentration of the corroding liquid by bubbling air through it are very materially reduced. The air which passes through the corroding liquid is broken up into a great number of fine bubbles by means of the porous cell[1] through which it passes and the accumulation on or contact of bubbles of air with the metal specimen under test is prevented by the watch glass used as a shield as shown in the figure. The stream of air bubbles serves also as a means for agitation of the corrosive liquid as well as of aëration.

A modification of the simple immersion method has been planned and the construction is now under way in which the attempt will be made to minimize the formation of any protective surface layer such as forms readily on certain types of alloys. Two cylindrical specimens mounted on spindles which can be rotated at any desired speed, will be immersed within the solution. One of the specimens will bear lightly against a brush or pad, the other being exposed freely to the liquid. It is to be expected that a specimen the surface of which is kept clean and free from any adhering corrosion products may behave quite differently from one which is not treated in this manner.

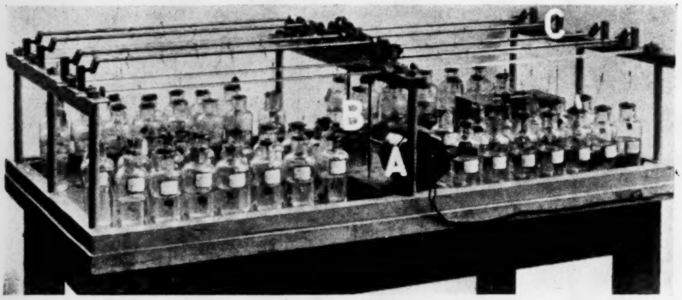


FIG. 5.—Apparatus for the Continuous Repeated Immersion Test.

A. Motor.
B. Reducing gears.
C. Cranks.

If it is desired to hasten the corrosive attack of the metal by electrolysis as mentioned above, the apparatus must be modified very considerably. Essentially, the apparatus needed is the same as the form sold by dealers of chemical apparatus and widely used in quantitative chemical analysis by electrolytic means. The form is well known and easily procurable. Further details may be obtained from the paper by R. J. Anderson and G. M. Enos presented at this annual meeting of the Society.[1]

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[1] The authors wish to credit the use of this device to J. F. Thompson and R. J. McKay. See "The Control of Motion and Aëration in Corrosion Tests," *Journal, Industrial and Engineering Chemistry*, Vol. 15, p. 1114 (1923).

Repeated Immersion.—Corrosion tests of this kind may be considered as one means for controlling aëration and are of two types, which differ, in that a timing device is used in one so that the immersion of the specimen takes place at stated intervals. Thus the metal is given opportunity to dry off between successive immersions. Aside from the device for timing the immersions, the apparatus developed for this test is essentially the same in the two cases.

Fig. 5 is a photograph showing the apparatus in use for the continuous or uninterrupted repeated immersion test. It consists essentially of a $\frac{1}{20}$-h.p. electric motor operating a series of eight cranks at a rather low speed by means of a series of reduction gears and a chain drive. A crank arm of a radius of $1\frac{1}{2}$ in. has been used and a speed of $\frac{1}{3}$ r.p.m. has been found very satisfactory. In a later form of the apparatus a 2-in. crank arm was selected as more satisfactory, and counterweights for balancing the combined weight of the specimens under test were inserted. Each specimen is supported by a silk thread, or other suitable means, attached to the crank by a loosely fitting hook, and passing over a loose wooden pulley on a stationary glass rod set parallel to the crank rod and on a level with the lowest point reached by the crank during its revolution. Fig. 6 shows both of these forms

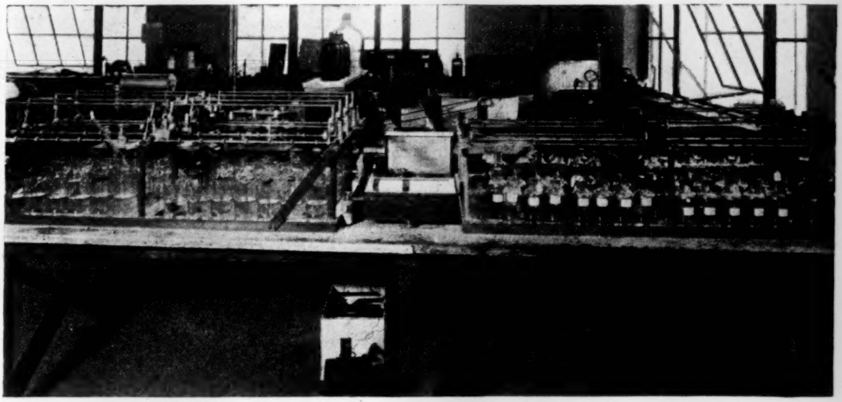

FIG. 6.—View of Bureau of Standards' Corrosion Laboratory Showing Set-Up for the Continuous (right) and the Interrupted (left) Repeated Immersion Test.

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[1] R. J. Anderson and G. M. Enos, "An Accelerated Electrolytic Corrosion Test," see p. 735, the present volume.—ED.

of repeated immersion apparatus as set up in the laboratory of the Bureau of Standards, the one at the left being the intermittent repeated immersion.

The timing device necessary for the interrupted repeated immersion test is illustrated in Figs. 7 and 8. This device consists of an 8-day clock to the dial of which is attached a ring of insulating material with small and large copper cups filled with mercury symmetrically placed. The large mercury cups correspond to about a 4-minute interval, while the small ones correspond to a 15-second interval. There are also two relays with accompanying condensers, two batteries to operate the relays and a disk made of insulating material in the face of which a split metal ring is embedded. The disk is attached to one of the crank bearings in such a manner that the axis of one crank of

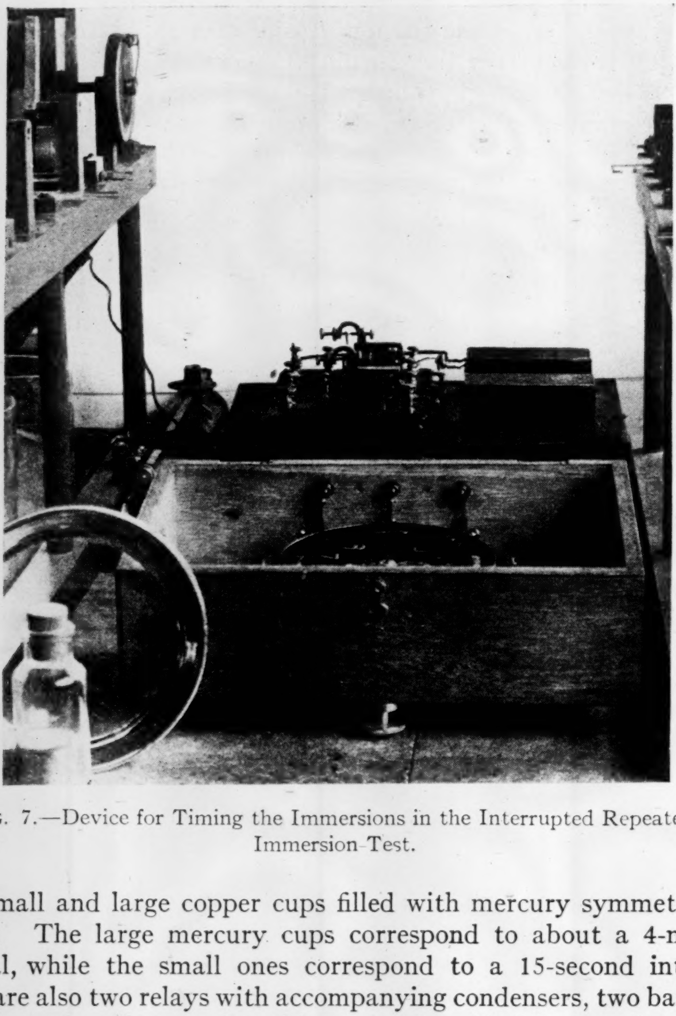

FIG. 7.—Device for Timing the Immersions in the Interrupted Repeated Immersion-Test.

the apparatus passes through the central hole on the disk and a metal trolley is attached to the end of this shaft and by the necessary connections makes contact between the mercury cups of the clock, the split metal ring of the disk, and one of the batteries.

In order to run the apparatus illustrated at the slow speed desired (about 1 revolution in 3 minutes) and in the meantime to obtain large enough torque, it was necessary to apply 50 volts to the armature and 110 volts to the field of the motor. It should be noticed, however, that instead of using two different currents, a greater gear reduction could be made and 110-volt current used for both the armature and the field. In this case, only one relay would be necessary.

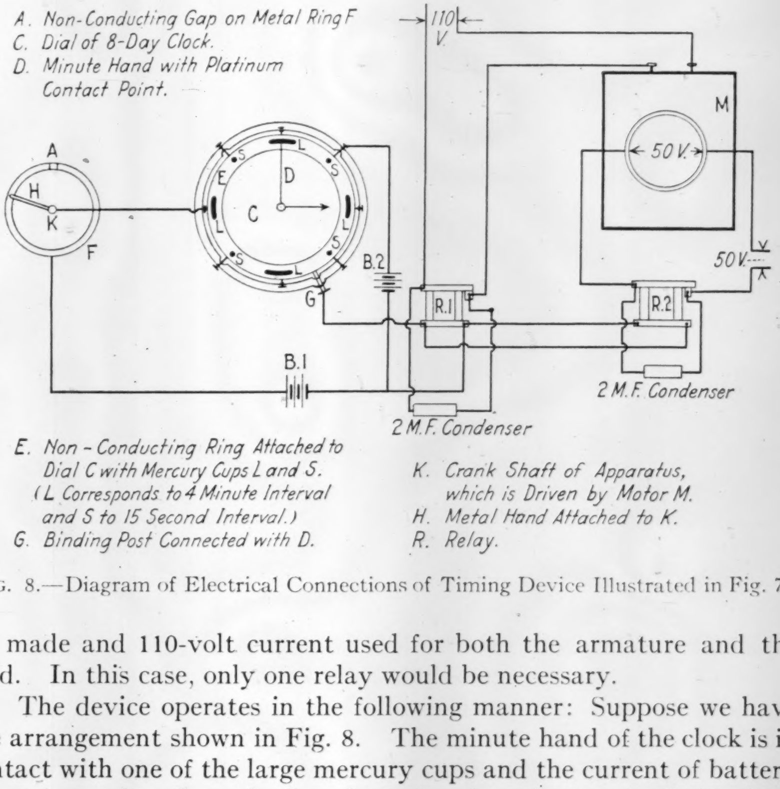
A. Non-Conducting Gap on Metal Ring F
C. Dial of 8-Day Clock.
D. Minute Hand with Platinum Contact Point.
110 V.
M
50 V.
A
H
K
F
S
L
E
D
C
B.2
G
50 V.
R.1
R.2
B.1
2 M.F. Condenser
2 M.F. Condenser
E. Non-Conducting Ring Attached to Dial C with Mercury Cups L and S. (L Corresponds to 4 Minute Interval and S to 15 Second Interval.)
G. Binding Post Connected with D.
K. Crank Shaft of Apparatus, which is Driven by Motor M.
H. Metal Hand Attached to K.
R. Relay.

FIG. 8.—Diagram of Electrical Connections of Timing Device Illustrated in Fig. 7.

The device operates in the following manner: Suppose we have the arrangement shown in Fig. 8. The minute hand of the clock is in contact with one of the large mercury cups and the current of battery No. 1 is passing through the minute hand to the frame of the clock and further through both relays to the metal ring and then through the trolley attached to the shaft and back to the same mercury cup. Thus both relays have closed the circuits necessary for the operation of the motor, thereby causing the rotation of the crank shafts of the apparatus. This will continue until the trolley strikes the non-conducting gap in the metal ring; at that moment the circuit is broken, the motor stops, and the specimens remain suspended in mid air. When the minute hand comes into contact with the next small mercury cup it will close the circuit of battery No. 2, which is completed through the clock and both relays. As a result, the motor will run for a short period of sufficient length (about 15 seconds) to "kick" the metal trolley from the non-conducting gap to a position on the metal ring corresponding to maximum elevation of specimens. Thus the device is ready for the next immersion. The number of immersions of any specimen is recorded by means of an automatic mechanical counter. The duration of the drying periods depends upon location of the large mercury cups. The period corresponding to the conditions shown in Fig. 8 is 15 minutes. The apparatus, although of a different form, serves the same general purpose as that described recently by Farnsworth and Hocker.[1]

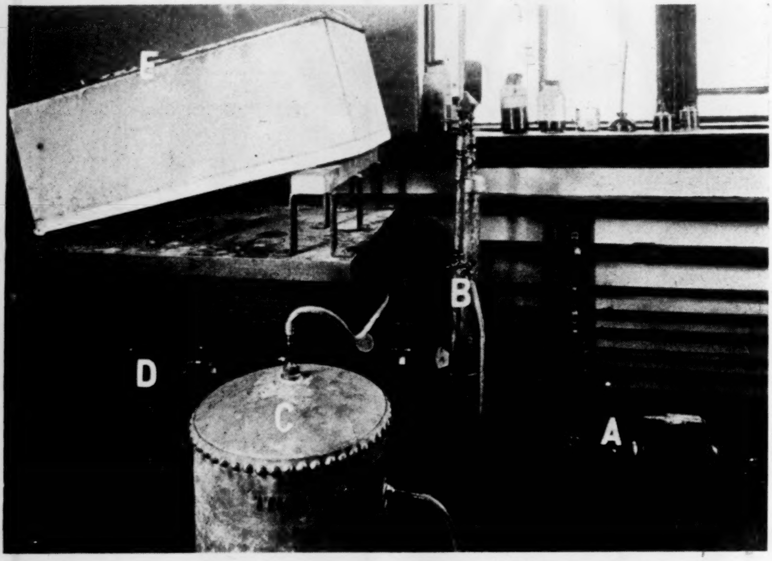

FIG. 9.—Spray or Mist Corrosion Apparatus, Bureau of Standards.

A. Motor and air compressor pump.
B. Connection for filter for removal of oil.
C. Reservoir tank.
D. Wash bottles.
E. "Mist box."

In the apparatus illustrated in Fig. 6 no arrangements for controlling the temperature of the test have been made. Any such

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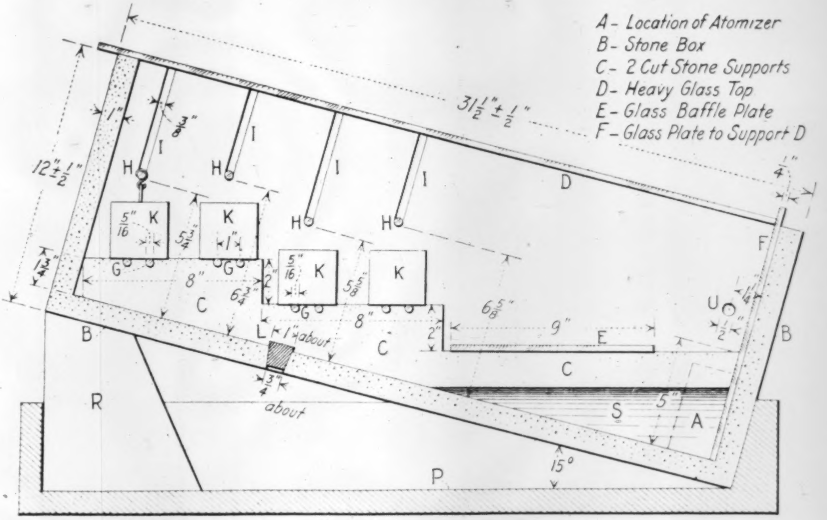
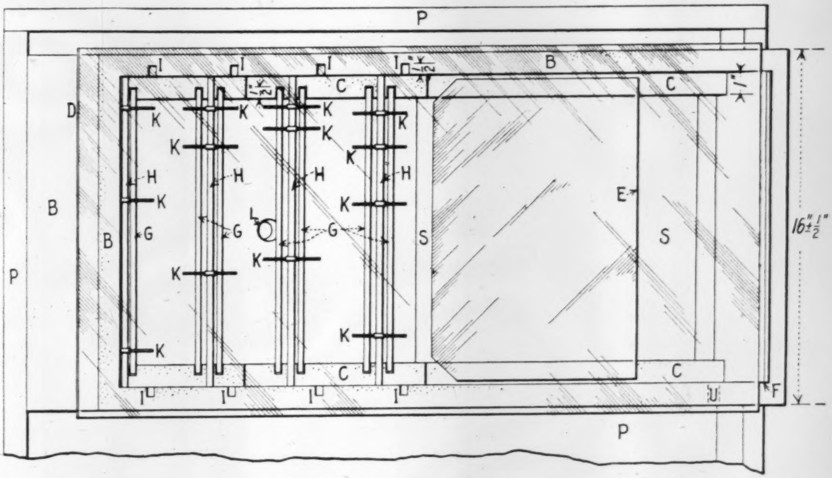
[1] F. F. Farnsworth and C. D. Hocker, "An Intermittent Immersion Test as an Aid in Evaluating Zinc Coats Plated on Iron and Steel," Am. Electrochemical Soc., preprint April meeting, 1924.


31½" ± ½"
12" ± ½"
1"
3/8"
1¾"
5/16"
5¾"
1"
8"
6¾"
2"
5/8"
6⅝"
9"
2"
1" about
¾" about
5"
¼"
½"
15°
A
B
C
D
E
F
G
H
I
K
L
P
R
S
U

A- Location of Atomizer
B- Stone Box
C- 2 Cut Stone Supports
D- Heavy Glass Top
E- Glass Baffle Plate
F- Glass Plate to Support D

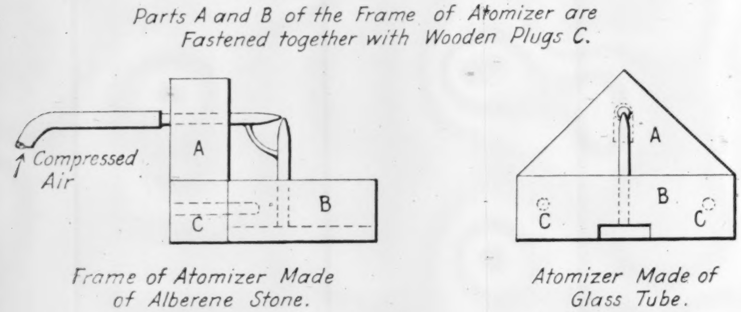
G - Glass Rods to Support Samples
H - Glass Rods; Overhead Supports for Samples
I - Slots for Glass Rods H
K - Samples
L - Opening for Exhaust
U - Hole for the Air Pipe.
P - Wooden Trough
R - Block to Support Box B
S - Salt Solution


16" ± ½"
1"
½"
1/12"
B
C
D
E
F
G
H
I
K
L
P
S
U

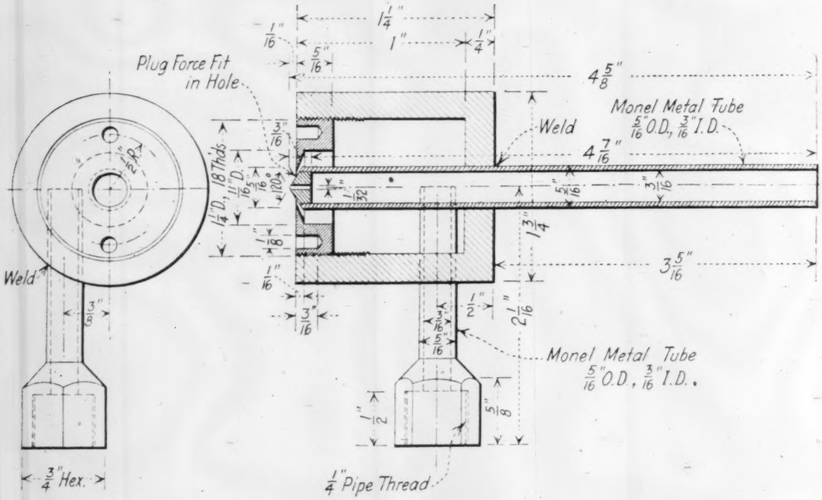
B- Stone Box.
C- Cut Stone Supports.
D- Heavy Glass Top.
E- Glass Baffle Plate.
F- Glass Plate to Support D.
G- Glass Rods to Support Samples.
H- Glass Rods; Overhead Support for Samples.
I- Slots for Glass Rods H
K- Samples.
L- Opening for Exhaust
P- Wooden Trough
S- Salt Solution.
U- Hole for the Air Pipe.

FIG. 10.—Diagram of "Mist Box" of Fig. 9.

arrangement will complicate the apparatus considerably. An approximation may be made by immersing the lower part of the containers of the solutions within a thermostatically controlled water bath somewhat similar to that shown in Fig. 2. Enclosing the entire apparatus within a "constant-temperature" compartment would be preferable, however, in many ways.


Parts A and B of the Frame of Atomizer are Fastened together with Wooden Plugs C.
Compressed Air
A
B
C
Frame of Atomizer Made of Alberene Stone.
A
B
C
C
Atomizer Made of Glass Tube.

(a) Glass atomizer.


1 1/4"
1/16"
1"
1/4"
5/16"
Plug Force Fit in Hole
4 5/8"
Monel Metal Tube 5/16" O.D., 3/16" I.D.
Weld
3/16"
4 7/16"
1 1/4" D., 18 Thds.
11/16" D.
5/16"
120°
1/32"
5/16"
3/16"
1 3/4"
1/8"
1/16"
3 5/16"
Weld
3/8"
3/16"
1/2"
2 1/16"
3/16"
5/16"
Monel Metal Tube 5/16" O.D., 3/16" I.D.
1/2"
5/8"
3/4" Hex.
1/4" Pipe Thread

(b) Adjustable metal atomizer (New Jersey Zinc Co.).

FIG. 11.—Two Forms of Atomizers Used in the Mist Corrosion Test.

Spray or Mist Corrosion.—The general character of this test is rather well known and descriptions of a suitable form of apparatus have been published previously.[1] The form of apparatus illustrated in Figs. 9 and 10 for this test is in close agreement with the previously published descriptions. Care must be taken to free the air from oil which may be carried over from the pump. This may be done by means of a filter of cotton wool, "settling" tank, and a series of wash bottles as is shown in Fig. 9. The wash bottles also serve to saturate the incoming air with water vapor so that the concentration of the corrosive solution within the "spray box" is changed only slightly.

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[1] J. A. Capp, "A Rational Test for Metallic Protective Coatings," *Proceedings*, Am. Soc. Testing Mats., Vol. XIV, Part II, p. 474 (1914). A. N. Finn, "Method of Making the Salt-Spray Corrosion Test," *Proceedings*, Am. Soc. Testing Mats., Vol. XVIII, Part I, p. 237 (1918), and U. S. Bureau of Standards *Circular No. 80*, "Protective Metallic Coatings for the Rust Proofing of Iron and Steel."

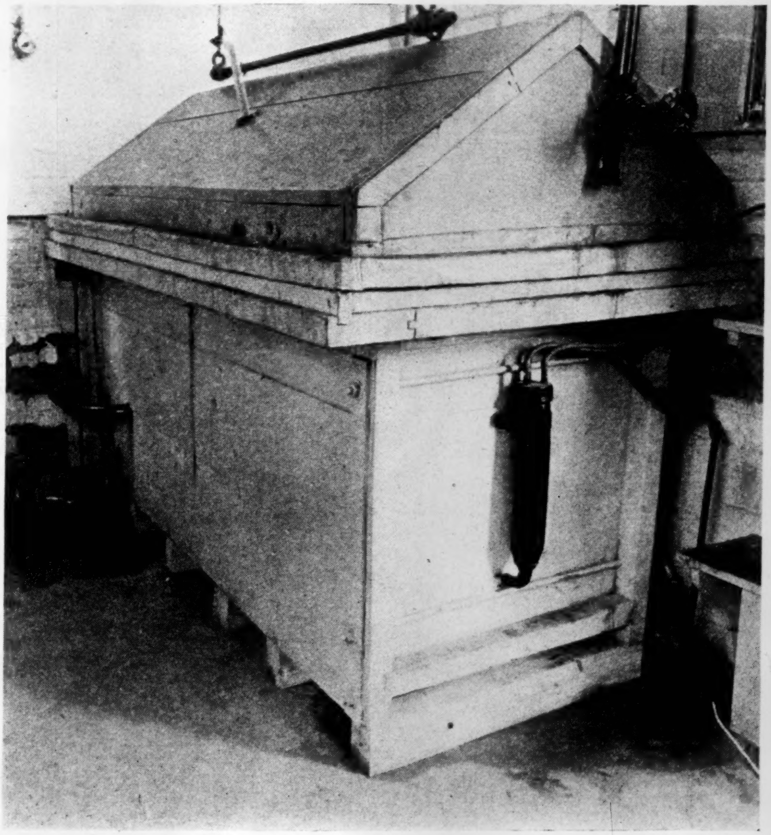

FIG. 12.—Exterior of Simulated Atmospheric Corrosion Tank Showing Gas Mixing Chamber and Inlet to Tank, Research Laboratory, New Jersey Zinc Co.

Another feature deserving mention is the "atomizer." For general "all around" use, glass is the only dependable material to use for this. Fig. 11 (*a*) shows a form of atomizer used which has proved successful and the means taken to keep it in good adjustment. For certain corrosion tests, atomizers constructed from a corrosion-resistant metal may be used. Fig. 11 (*b*) shows one which has proved very satisfactory in service, the characteristic features being the adjustable annular orifice used and the tangential whorling mist which is produced by this form of atomizer.

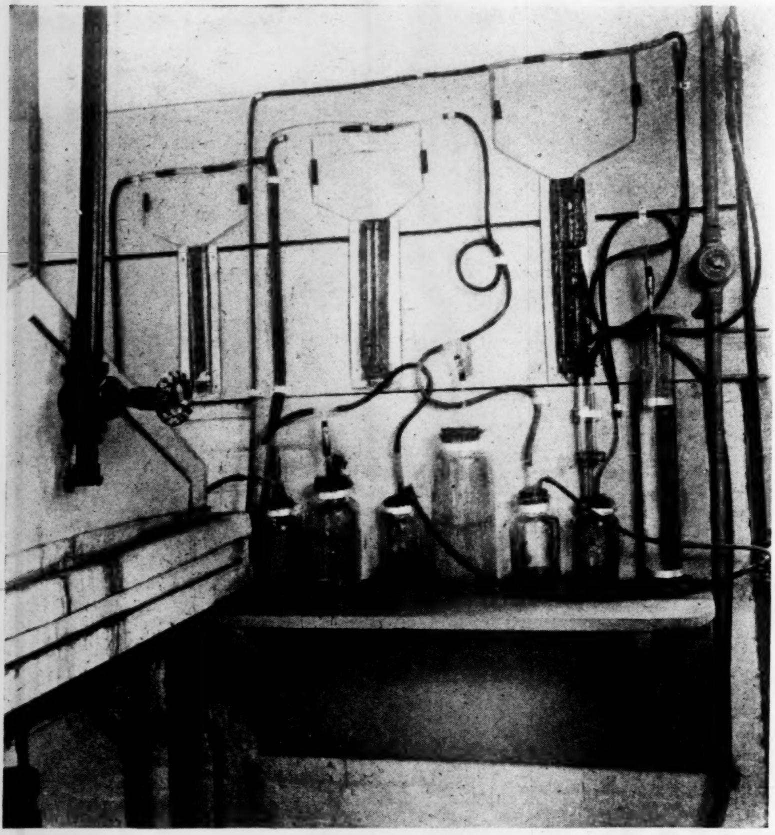

FIG. 13.—Flow Meters Used in the Simulated Atmospheric Corrosion Test for Controlling the Supply of Air, Carbon Dioxide, and Sulfur Dioxide.

If it is desired to conduct the mist corrosion test at a constant temperature, heating coils may be placed in the solution within the corrosion box if the solution used has only a mildly corrosive action. In cases of more severe corrosion it would be necessary to enclose the corrosion box within a heat-insulated chamber. In the apparatus pictured in Fig. 9 no arrangements for controlling the temperature of the test have been made, as yet.

Simulated Atmospheric Corrosion.[1]—In this test an attempt has been made to imitate those atmospheric effects which are generally considered to be the most important of the various atmospheric agencies responsible for corrosion. The test, which is planned for coated metals in particular, is carried out in three steps: (1) an exposure to a warm moist atmosphere containing relatively large amounts of SO_2 and CO_2 gases for 10 hours; (2) thorough washing with water in the form of a coarse spray for 2 hours, and (3) drying in ordinary atmosphere at room temperature for 12 hours. This entire opera-

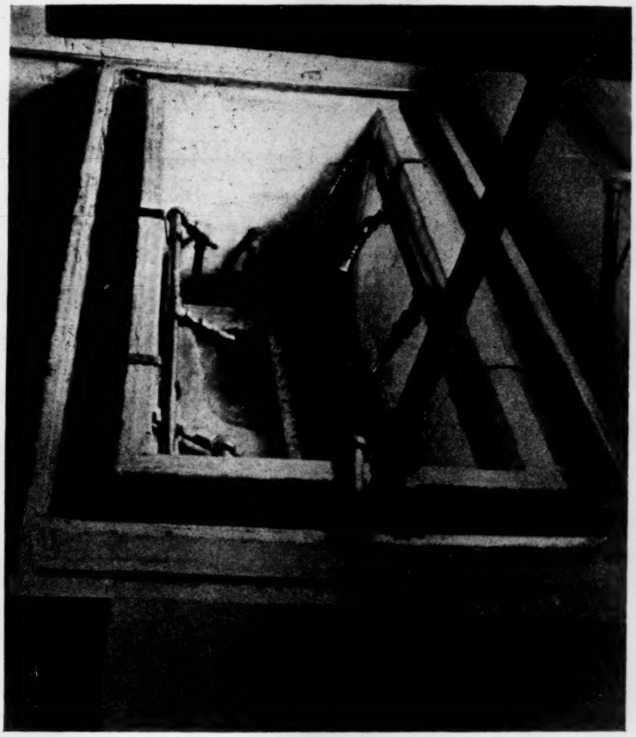

FIG. 14.—Interior of Corrosion Tank of Fig. 12, Showing the Water-Spraying Device in Place for Washing the Specimens.

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[1] Contribution from the Research Laboratory, New Jersey Zinc Co., Palmerton, Pa. In view of the fact that this test is still in the development stage a complete description of its development, details of its operation and character of the results secured has been withheld. This information will be made the subject matter of a paper to be published shortly in the technical press by W. H. Finkeldey.

tion constitutes one cycle and the number of cycles required to produce pronounced rusting of the steel base is taken as a measure of the ability of the material to withstand atmospheric corrosion. The coatings are examined for failure during the drying period.

An acceleration of ordinary atmospheric corrosion rate is secured by increasing the moisture, temperature, corrosive gas concentration, and rainfall to amounts above that usually obtained in the atmosphere and by arranging for frequent repetition of the attacks.

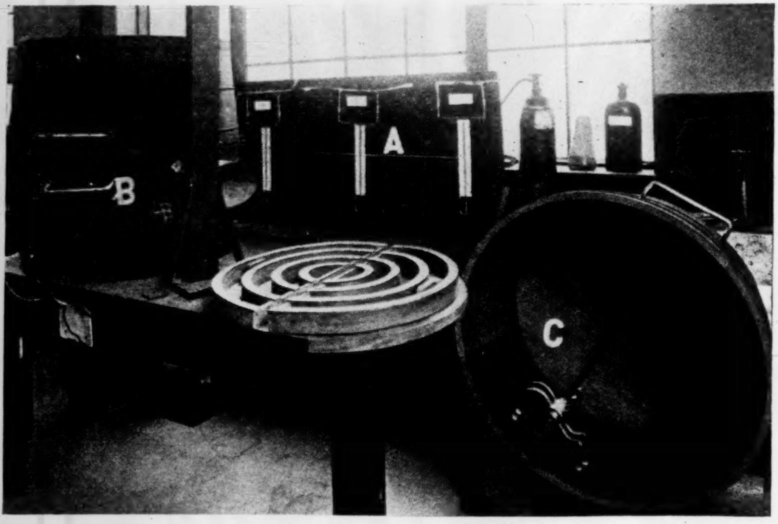

FIG. 15.—Small-Scale or Laboratory-Size Apparatus for the Simulated Atmospheric Corrosion Test, Bureau of Standards.

A. Flow meters for controlling the gas flow to tank *B*.
C. Cover containing whorling spraying device to replace the other cover when the washing period is started.

The test as conducted on a "plant-size" scale is carried out in a lead-lined wooden tank approximately 68 in. long, 38 in. wide and 44 in. high, constructed of cypress planks 2 in. thick, as shown in Fig. 12. The tank cover, also lead lined, fits into the trough-like arrangement on the sides, which is filled with water when the tank is in operation, an effective gas seal thus being formed. The tank is filled to a height of 6 in. with water which is heated by three special electric heaters. An atmosphere, consisting of 100 volumes of air, 5 volumes of CO_2 and 1 volume of SO_2, controlled by flow meters (Fig. 13), is admitted to the tank at one end just above the water line, and by means of a false bottom in the tank the air and gas mixture is made to pass over the surface of the heated water for the entire length of the tank before coming in contact with the specimens; thus the atmosphere is warmed and saturated with water vapor. The concentration of the gases is admitted to the tank at the approximate rate of 6.4 liters per minute. The temperature of the water is regulated so as to give an atmospheric temperature of 55° C. in the tank in the proximity of the specimens.

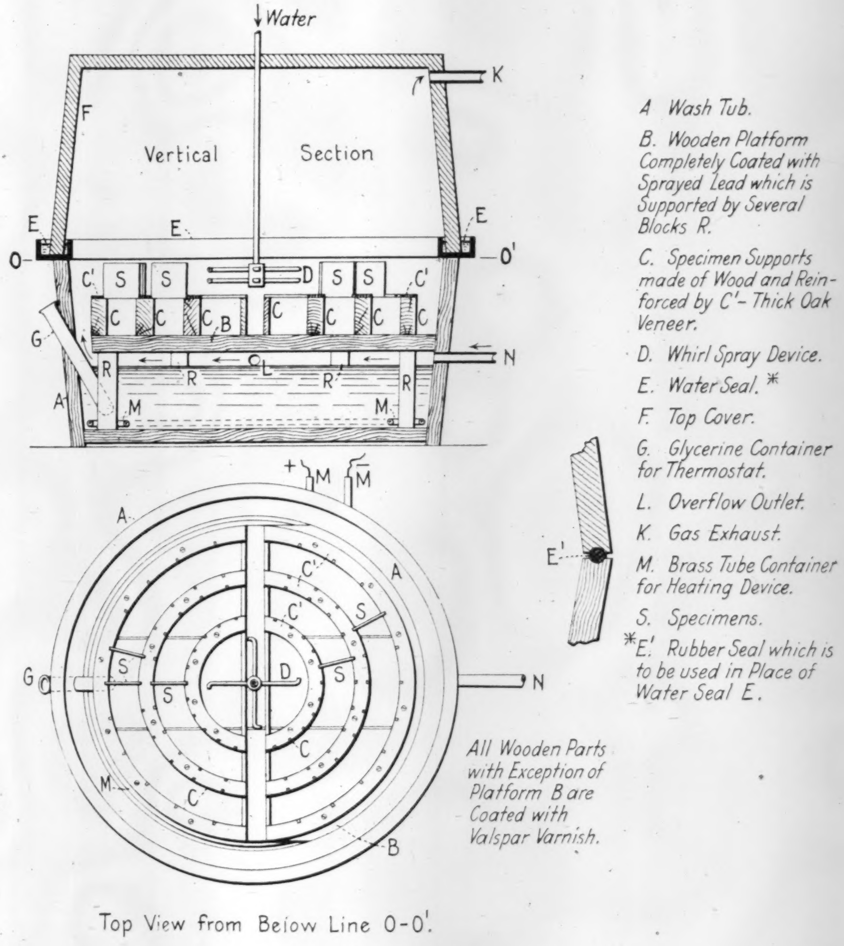
Water
K
F
Vertical
Section
E
E
E
O
O'
C'
S
S
D
S
S
C'
C
C
C
B
C
C
C
C
G
N
R
L
R
R
R
A
M
M
+
M
M
A
C'
A
C'
S
G
S
D
S
S
N
C
M
C'
B
E'
Top View from Below Line O-O'.
A Wash Tub.
B. Wooden Platform Completely Coated with Sprayed Lead which is Supported by Several Blocks R.
C. Specimen Supports made of Wood and Reinforced by C'– Thick Oak Veneer.
D. Whirl Spray Device.
E. Water Seal. *
F. Top Cover.
G. Glycerine Container for Thermostat.
L. Overflow Outlet.
K. Gas Exhaust.
M. Brass Tube Container for Heating Device.
S. Specimens.
*E'. Rubber Seal which is to be used in Place of Water Seal E.
All Wooden Parts with Exception of Platform B are Coated with Valspar Varnish.

FIG. 16.—Diagram of Section of Apparatus of Fig. 15.

The tank is provided with an exhaust large enough to prevent the pressure from building up and to permit a continual change of the atmosphere in the tank, thus keeping the gas concentrations constant. Fig. 14 shows an interior view of the tank with the water spray device in place. A drain is provided in the tank at the proper level to provide for the outflow of water during the washing period.

The specimens are mounted upright in slits sawed in wooden strips resting on the false bottom of the tank. Holes are bored in the same strips for mounting wire specimens. The cut edges of the test specimens are protected with a bitumistic enamel, applied either in the molten state or dissolved in a volatile solvent, in order to prevent rust stains from contaminating the surface of the specimen proper.

A small-scale apparatus for conducting this test on a laboratory rather than "plant" scale is shown in Figs. 15 and 16. The principles of operation are the same as those already given. Cypress laundry tubs are used for the container and covers. The rotary water spray necessary for the washing operation is permanently installed in the second tub which is used to replace the first cover when the spraying period is started.

In the apparatus described and illustrated in the foregoing discussion, details of construction obviously cannot be given. Most of these necessary for reproducing the apparatus are given in the figures, however. If the principles underlying the various testing methods are fully appreciated, the main purpose of the authors will have been accomplished.

AN ACCELERATED ELECTROLYTIC CORROSION TEST[1]

BY ROBERT J. ANDERSON[2] AND GEORGE M. ENOS[3]

INTRODUCTION

The selection of metals and alloys for withstanding corrosive conditions should be based on reliable and adequate tests, but so far no generally acceptable method for corrosion testing has been developed. Ordinarily, determination of the resistance to corrosion of a metal or alloy in any liquid requires immersion tests in that medium over a period of time. Long-time immersion tests yield satisfactory data, but require too much time, and an adequate accelerated test is undoubtedly needed. This paper describes an accelerated electrolytic corrosion test developed by the U. S. Bureau of Mines in cooperation with the Carnegie Institute of Technology, in the course of research on the corrosion of metals and alloys in acid mine waters. The results are presented in correlation with data from long-time immersion tests. W. A. Selvig and one of the authors[4] had previously made corrosion tests on metals and alloys in flowing acid mine waters, and the authors[5] had studied the microstructure of these corroded materials. Still further work, in collaboration with J. R. Adams,[6] on the accelerated corrosion testing of metals and alloys in acid mine waters, has been discussed elsewhere.

Since corrosion is regarded as being either chemical or electrochemical, an accelerated test might be either chemical or electrolytic. Either test would be based primarily on the assumption that corrosion is essentially a process of oxidation, which may take place by direct reaction of a metal with oxygen (chemical corrosion) or by electrolytic means (electro-chemical corrosion). Chemical corrosion can probably be accelerated mechanically (by agitation), and by increasing the oxygen content of the solution. Electrolytic corrosion can be accelerated by both electrolytic and chemical means. The bulk of the results given here are based on electrolytic tests, although some work was done on chemical tests.

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[1] Published by permission of the Director of the U. S. Bureau of Mines, Department of the Interior.

[2] Formerly Metallurgist, U. S. Bureau of Mines, Experiment Station, Pittsburgh, Pa.

[3] Instructor in Metallurgy, University of Cincinnati, Cincinnati, Ohio.

[4] W. A. Selvig and G. M. Enos, "Corrosion Tests on Metals and Alloys in Acid Mine Waters from Coal Mines," *Bulletin No. 4*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh (1922).

[5] R. J. Anderson and G. M. Enos, "Microstructural Aspects of Metals and Alloys Corroded by Acid Mine Waters," *Bulletin No. 5*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh (1923).

[6] R. J. Anderson, G. M. Enos, and J. R. Adams, "Accelerated Corrosion Testing of Metals and Alloys in Acid Mine Water," *Bulletin No. 6*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh (1923).

Several investigators have suggested that chemical and electrochemical corrosion are the same thing. Desch and Whyte[1,2] submit that there is no difference between electrolytically stimulated and natural (chemical) corrosion; this view is shared by us, for we have shown that these two actions are the same qualitatively, but not necessarily quantitatively. Bengough and Stuart[3] hold that corrosion may be either chemical or electrolytic, and they cite the work of Gates[4] who showed that the corrosion of metals can take place in non-electrolytes, as proof that an electrolyte is not required for corrosion.

The results of various attempts to develop accelerated corrosion tests need not be reviewed here. The most promising method is the anodic corrosion test, in which the sample to be tested is made the anode in a cell containing the corroding medium as electrolyte, and platinum wire is used as the cathode. A small current is passed through the cell, and the corrosion loss is determined for any given period of time. Laboratory tests of this kind have been made by many investigators, and the work at Cornell University may be particularly noted.[5] However, this type of test has not hitherto been correlated with long-time immersion tests.

PRELIMINARY EXPERIMENTS

We first made experiments using a chemical corrosion test, but the results were negative. Briefly, metals and alloys were suspended in jars containing the corroding medium (acid mine water), and air was bubbled through at a uniform rate. No acceleration of the corrosion rate over that of the simple immersion test was obtained. Because of difficulties inherent in the set-up employed, and the impracticability of controlling these difficulties, this test was abandoned. However, these negative experiments do not preclude the devising of an accelerated test that is strictly chemical. Oxidizing solutions, or

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[1] C. H. Desch and S. Whyte, "The Micro-Chemistry of Corrosion: Part I—Some Copper-Zinc Alloys," *Journal*, Inst. of Metals, Vol. 10, pp. 304–323 (1913).

[2] S. Whyte and C. H. Desch, "The Micro-Chemistry of Corrosion: Part II—The Alpha Alloys of Copper and Zinc," *Journal*, Inst. of Metals, Vol. 11, pp. 235–245 (1914).

[3] G. D. Bengough and J. M. Stuart, "The Nature of Corrosive Action, and the Function of Colloids in Corrosion, with an Appendix on Terms Used in Colloid Chemistry," Sixth report to the Corrosion Research Committee of the Institute of Metals, *Journal*, Inst. of Metals, Vol. 28, pp. 31–114 (1922).

[4] C. B. Gates, "The Replacement of the Metals in Non-Aqueous Liquids and the Solubility of Metals in Oleic Acid, *Journal*, *Phys. Chem.*, Vol. 15, pp. 97–146 (1911).

[5] B. E. Curry, "Electrolytic Corrosion of the Bronzes," *Journal*, *Phys. Chem.*, Vol. 10, pp. 474–499 (1906), and a series of related papers by Lincoln, Rowland, *et al.*, in later volumes of the journal.

solutions saturated with oxygen, may possibly be found that will yield the desired rate of acceleration, corroding a metal or alloy in the same manner, in direct proportion, and much faster than the medium in which the metal is to be used. The conversion factor from accelerated tests of this kind to long-time immersion, or service, tests would require determination.

Since the previous work by Curry, Lincoln, Rowland, and others had indicated that there were good possibilities for developing an accelerated electrolytic corrosion test, we repeated part of Curry's[1] work in order to ascertain whether his results could be duplicated.

The fundamental principles of electro-chemistry, on which this accelerated electrolytic corrosion test is based, are here stated briefly. According to Faraday's law, chemically equivalent quantities of ions are liberated by the passage of equal quantities of electricity; that is, the quantities of different substances that separate at the electrodes throughout the circuit are directly proportional to their equivalent weights and are independent of the concentration and temperature of the electrolyte, the size of the electrodes, and all other conditions. If a dilute (aqueous) solution of sulfuric acid be electrolyzed, using insoluble electrodes, oxygen is given off at the anode or positive electrode, and hydrogen appears at the cathode or negative electrode. Whether the anode is soluble or insoluble, evidently the same amount of oxygen will be liberated from the electrolyte by the passage of a given amount of electricity and will be available for oxidizing.

Now, if a metal be made the anode in a cell containing any electrolyte, the imposition of an electric current will cause the release of hydrogen (or its equivalent) at the cathode as neutral gaseous hydrogen (H°). The negative ions of the electrolyte give up their charges at the anode, and the metal passes into solution as positive ions. The solution of the metal is due to interaction of metallic atoms with the nascent atoms from the electrolyte. If the anode be insoluble in the electrolyte, then the atoms from the electrolyte, which are formed at the anode from negative ions, do not interact with atoms of the anode, and the electrolyte atoms are deposited, evolved as gas, or react with the electrolyte according to the conditions.

Faraday's law does not define the amount of electrical energy necessary to effect the solution of a given amount of material from the anode, but it does define the quantity of electricity necessary to cause the deposition (or release) of the constituents of the electrolyte. Thus, for each gram of hydrogen liberated at the cathode (*e. g.*, in the system sulfuric acid and water), 96,540 coulombs of electricity are required.

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[1] B. E. Curry, *Loc. cit.*

Or, if the solution be copper sulfate, an amount of copper (31.8 g.) equivalent to 1 g. of hydrogen will be deposited at the cathode.

When a metal is made the anode in a corroding medium, then, and an electric current passed, the number of attacking oxidizing atoms (resulting from negative ions) made available per unit of time is greater because the electrolyte decomposes faster than if no current were imposed. Also, increasing the amount of current passed generally increases the number of atoms released per unit of time, because of increased rate of decomposition of the electrolyte. Immediately on passage from the ionic to the atomic state, the nascent atoms formed at the anode are unstable and tend to react with the metal atoms of the anode, and the atoms from the electrolyte may be deposited, be evolved as molecular gas, or interact with the electrolyte. An imposed current will not necessarily send into solution a definite amount of the anode, but it accelerates the dissolving of the anode by increasing the oxidizing power of the solution.

In the electrolytic refining of blister copper, the anodes, impure copper plates, are placed in an electrolyte of dilute sulfuric acid and copper sulfate. In this case, copper goes into solution at approximately the same rate at which it is deposited. When copper is deposited from solutions obtained by leaching copper ores, an insoluble anode is required, and duriron, hard lead, and other relatively insoluble alloys are used. The nature of the anode only indirectly affects the decomposition of the electrolyte. In the accelerated electrolytic test, the amount of deposition is of secondary interest. The rate of solution of the anode is to be accelerated, and this is accomplished by increasing the oxidizing power of the solution. In the present experiments the best results for the accelerated electrolytic test were obtained at about the same current densities as those used in copper refining. Thus, a current density of about 0.18 ampere per sq. dcm. is found suitable for the accelerated test; this is equivalent to 16.7 ampere per sq. ft. In copper refining the current density employed at different plants varies between 12 and 34 ampere per sq. ft.

In repeating Curry's work, we made experiments on copper-tin alloys of various compositions to show how near our results could be checked with his, and that the general method of attack was applicable to the problem of developing an accelerated electrolytic corrosion test. However, we had to make changes in technique and to improve the apparatus employed. Detailed results of these experiments need not be given here; they agreed with those of Curry. However, a study of the experimental data of Curry shows that he did not consider the various factors that affect corrosion rates in the electrolytic test, and in our work we examined in some detail those factors considered most important.

FACTORS AFFECTING LOSS IN WEIGHT BY ACCELERATED ELECTROLYTIC CORROSION

A number of factors affect results in accelerated electrolytic corrosion testing, but many of them are of minor importance and may be disregarded. It is, of course, recognized that the factors affecting any corrosion process are numerous, but these can not be discussed even in a general way in the present paper. Given a specific metal or alloy and a specific electrolyte, the variable factors that are of greatest importance in affecting corrosion rates in the accelerated electrolytic corrosion test include the following: (1) current density; (2) time of exposure; (3) temperature; (4) speed of rotation of the test piece; and (5) the nature of the coatings formed. The latter depends on the chemical composition and physical condition of the metal or alloy, the chemical composition of the corroding medium, and, to a lesser extent, on the first four factors just given.

Current Density.—Some tests were made on the accelerated electrolytic corrosion of 90:10 and 70:30 Cu-Sn alloys, using 6.5-per-cent sodium nitrate as the electrolyte, with the current density varied over the range 0.179 to 2.64 ampere per sq. dcm. In these runs the amperage was maintained constant, and the current density was varied by varying the submerged areas of the test pieces. Since the current density is the result of amperage divided by the area from which the current passes, either the amperage or immersed area may be varied in order to vary the current density. The loss in weight, of course, is not necessarily proportional to the quantity of electricity imposed, *i. e.*, to the amperage.

Additional runs were made with a number of different metals and alloys in given electrolytes and a typical commercial alloy (naval brass) in several electrolytes and with the current density varied over the approximate range 0.125 to 5.8 ampere per sq. dcm. For these tests, the following metals and alloys were corroded in dilute sulfuric acid (15,760 p.p.m.); 90:10 and 65:35 Cu-Sn alloys; various brasses, including a high brass (67:33 Cu-Zn), a low brass (80:20 Cu-Zn), a naval brass (60:39:1 Cu-Zn-Sn), and Admiralty metal (70:29:1 Cu-Zn-Sn); and copper and iron. The copper-tin alloys were in cast form, and the other materials in sheet form. Naval brass sheet (60:39:1 Cu-Zn-Sn) was also corroded in the following solutions: Edna No. 2 mine water (free acidity 2020 p.p.m.); dilute sulfuric acid (15,760 p.p.m.); sea water, 4 per cent NaCl; sodium-chloride solution, 8 per cent NaCl; and sodium-hydroxide solution, 1 per cent NaOH. In these runs, the immersed areas of the test pieces were maintained as constant as possible, and the current density was varied by varying the amperage. The results of these experiments have been reported in detail elsewhere; they may be summarized as follows: With a constant current density of less than 0.2 ampere per sq. dcm., all other factors being constant, the results so obtained are comparable for different materials in the same electrolyte or for the same material in different electrolytes, but this does not hold true for all tests at higher current densities. Small variations in current density are permissible. The current density used in most of the experimental work was approximately 0.18 ampere.

Time Period of Exposure.—Experiments were made with suitable alloys and corroding media to determine the effect of varying the period of exposure over the range 15 minutes to 8 hours. The loss in weight in the accelerated electrolytic test is not necessarily a linear function of the time, since films or coatings formed may so inhibit corrosion as to change the time curve. However, for testing purposes, the corrosion loss may in general be regarded as a linear function of the time, within limits.

Shape of the Test Piece.—Experiment showed that the shape of the test piece had no effect on the corrosion rate.

Temperature.—Experiments on the effect of temperature on the loss in weight were not completed, but preliminary results indicated that increasing the temperature tends to increase the loss.

Speed of Rotation.—Experiments on the effect of speed of rotation of the test piece were not completed, but apparently the effect of increasing the speed would be to increase the loss, within limits.

General Discussion.—Some additional points brought out in these preliminary tests are mentioned below:

With regard to acceleration in different electrolytes, the tests of naval brass in five electrolytes show that the weight losses in the different electrolytes are straight-line functions of the current density. Since a low current density, for example, 0.2 ampere per sq. dcm., gives a sufficiently large loss in a fairly short time, and since at current density of less that 0.2 ampere the corrosion losses for all the materials tested in all the electrolytes are straight-line functions, it was decided to use this value. Variations of from 0.15 to 0.30 ampere are no doubt permissible. It is, however, practicable to corrode many alloys at a higher current density than 0.2 ampere, thus greatly accelerating the corrosion rate. It should not be thought that the loss for any material in a given solution will be the same as the loss for another material in the same solution, but rather that the different losses are directly proportional to the current density. Hence, if the same current density be employed in comparative tests of the corrosion rates of different materials in the same electrolyte, then the losses will be different in amount but comparable. Different materials in the same electrolyte show irregular losses at the higher current densities, owing to the formation of films and coatings. Detailed observations on the behavior of the electrolytes, the formation of precipitates, and of coatings on the test samples cannot be taken up here.

It is well to observe the fall in potential in each cell, since when the number of ions in the solution decreases and the solution tends to become exhausted, the voltage drop increases.

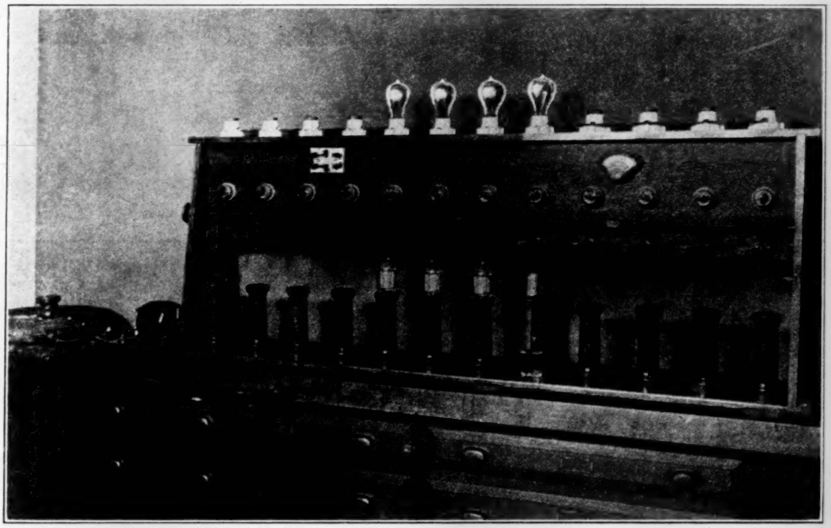

FIG. 1.—Electrolytic Cabinet for Accelerated Corrosion Testing, U. S. Bureau of Mines Model.

The results of the preliminary tests may be summarized briefly as follows: Accelerated electrolytic tests may be duplicated by independent workers. The effects of variable factors that influence results were examined, and it is found that a low current density, say 0.2 ampere per sq. dcm., should preferably be used in order to insure comparable results. The variable factors of time, temperature, speed of rotation, and composition of the electrolyte should be closely controlled. Observations as to the behavior of the electrolytes and formation of coatings should be correlated with the other data.

Technique of Accelerated Electrolytic Testing

Equipment for making accelerated electrolytic tests may be of very simple construction. The apparatus developed by the U. S. Bureau of Mines for such tests is shown in Fig. 1. The wiring diagram is shown in Fig. 2. Any simple type of electrolytic-analysis apparatus may be employed, however, and as many cells as are desired can be used. The apparatus in Fig. 1 is equipped with 12 rotating anode connections, and these may be used independently or all together as desired. It is ordinarily necessary to maintain the speed of rotation constant for groups of runs, and some speed-controlling device should be employed. Thus, the rotating anode spindles may be driven by a variable speed motor, or the speed of a constant-speed motor can be varied by a rheostat. The former is preferable. The imposed current is passed through the cells in series, and is regulated through a lamp-bank resistor. The cells are heavy-walled glass beakers, of 500-cc., or more, capacity. The cathodes are platinum wires.

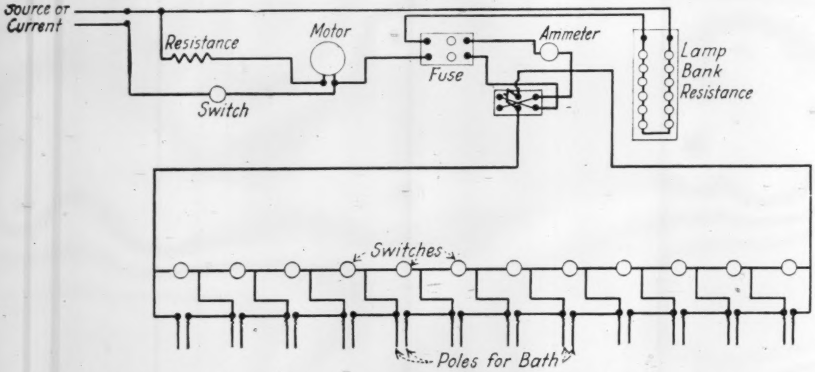

Fig. 2.—Wiring Diagram of Apparatus for Accelerated Corrosion Testing.

Samples for test are cut to any convenient size, and in the preliminary work described above, an area of about 14 sq. cm. was employed for exposure to the corroding medium. The weight of the test piece may be up to about 60 g. The surface of the test piece should be in the same condition as it is to be when used in service, *e. g.*, if a bronze is to be used as a machined part in a mine pump, the test piece should be machined; if a rough sand casting is to be used in service, the test piece should be a rough cast specimen. The test piece should be run for a period of time sufficient to yield a weighable loss; in testing very non-corrosive materials, eight hours is long enough to determine corrodibility. Most commercial metals and alloys will show a decided loss in 8 hours. The time factor will depend also on the nature of the electrolyte. The electrolyte employed should be the same as the corroding medium (or comparable with it) in which the metal or alloy is to be used in service. Accurate record should be kept of the weight of the test piece before and after corrosion, the area of the exposed portion, the current imposed, the voltage drop per cell, the chemical analysis of the test piece, the chemical analysis of the electrolyte, and the nature of the coatings and precipitates formed. The corrosion loss may be expressed conveniently as loss in milligrams per square centimeter per 24 hours. It is desirable to analyze the coatings and electrolytes after corrosion. After the test pieces have been cleaned—preferably by rubbing with a stiff bristle brush in running water—and dried, they should be carefully examined with the naked eye and the microscope.[1]

A study of the information obtained from the accelerated electrolytic corrosion test, properly carried out, will give qualitative and quantitative data as to the corrosion rate of any metal or alloy in any electrolyte. The data are readily translatable into terms of service corrosion, and it is this fact which recommends this test so strongly as an accelerated test.

CORRELATION OF LONG-TIME IMMERSION TEST AND ACCELERATED TEST IN ACID MINE WATERS

It remains now to take up the application of the test to practical corrosion problems. Correlation of accelerated electrolytic tests and long-time immersion tests were made with 42 metals and alloys corroded in acid mine water. It was found that the results obtained by this test in a few hours are comparable to long-time immersion test results obtained after months of exposure to a corroding medium. Most of the metals and alloys tested in the long-time immersion runs made by W. A. Selvig and one of the authors[2] were tested by the accelerated electrolytic corrosion method. Tests were carried out in three mine waters, but only those in one need be included here, *i. e.*, water from the Edna No. 2 mine of the Hillman Coal and Coke Co., at Wendel, Westmoreland County, Pa. The following factors were held constant within small limits: speed of rotation of test pieces, 140 r.p.m.; temperature, 20 to 25° C. (ordinary room temperature); current imposed, 0.025 ampere; area submerged, 14 sq. cm.; and period of test, 8 hours.

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[1] Since the present paper was written, the accelerated test has been improved, particularly as to details of manipulation, and the latest preferred technique of testing is described in the Report of Committee B-3 on Corrosion of Non-Ferrous Metals and Alloys.

[2] W. A. Selvig and G. M. Enos, *Loc. cit.*

TABLE I.—COMPARATIVE LOSS IN WEIGHT OF TEST PIECES IN ACCELERATED ELECTROLYTIC CORROSION TEST, AND LONG-TIME IMMERSION TEST, FOR 42 METALS AND ALLOYS IN EDNA NO. 2 MINE WATER

Designation	Chemical Composition, per cent[1]	Test Piece Number[2]	Area of Test Piece, sq. cm.	Weight, g.		Loss in Weight, g.	Loss per Square Centimeter per 24 Hours in Accelerated Test, mg.	Loss per Square Centimeter per 24 Hours in Long-time Exposure Test, mg.[3]
				Before Immersion	After Immersion			
			BRASSES					
Rolled high brass[4]	Cu 66.55 Zn 33.45	16 *a* 16 *b*	13.94 13.94	8.3854 8.9195	7.9962 8.5251	0.3892 0.3944	83.7 84.9	
		Average	.....	....	....	.....	84.3	7.30
Rolled low brass[4]	Cu 80.09 Zn 19.91	19 *a* 19 *b*	13.96 13.97	8.7062 8.0859	8.3600 7.7083	0.3462 0.3776	74.5 81.1	
		Average	.....	....	....	.....	77.8	7.17
Rolled naval brass[4]	Cu 60.4 Zn 38.83 Sn 0.77	22 *a* 22 *b*	14.00 13.98	9.0955 8.4606	8.7582 8.1082	0.3373 0.3524	72.3 75.8	
		Average	.....	....	....	.....	74.1	7.11
Rolled brass (Admirality metal), grain size 0.025 mm.	Cu 70.80 Zn 28.06 Sn 1.14	28 *a* 28 *b*	13.98 13.97	9.3006 9.5075	8.9739 9.1462	0.3267 0.3613	70.2 77.6	
		Average	.....	....	....	.....	73.9	7.07
Rolled brass (Admirality metal), grain size 0.035 mm.	Cu 71.38 Zn 27.36 Sn 1.26	64 *a* 64 *b*	13.98 13.97	9.0871 9.4897	8.7429 9.1332	0.3442 0.3565	74.0 76.5	
		Average	.....	....	....	.....	75.3	6.80
Rolled brass (Admirality metal), grain size 0.075 mm.	Cu 71.46 Zn 27.42 Sn 1.12	67 *a* 67 *b*	13.96 13.95	9.8311 9.6915	9.4567 9.3158	0.3744 0.3757	80.5 80.7	
		Average	.....	....	....	.....	80.6	6.72
Rolled manganese brass	Cu 57.95 Sn 0.47 Zn 41.02 Pb trace Fe 0.55	46 *a* 46 *b*	14.01 14.02	11.5262 10.9011	11.2066 10.5861	0.3196 0.3150	68.3 67.4	
		Average	.....	....	....	.....	67.9	6.66
			BRONZES					
Cast bronze	Cu 89.8 Sn 9.7 Pb 0.5	79 *a* 79 *b*	13.97 13.95	23.5448 22.1126	23.3728 21.9375	0.1720 0.1751	37.0 37.8	
		Average	.....	....	....	.....	37.4	2.12
Rolled bronze	Cu 98.51 Sn 1.49	55 *a* 55 *b*	13.98 13.95	9.4695 9.6174	9.1344 9.2577	0.3351 0.3597	72.0 77.3	
		Average	.....	....	....	.....	74.7	7.03
Rolled phosphor bronze[4]	Cu 94.4 Sn 5.5 P 0.1	58 *a* 58 *b*	14.01 14.03	8.9089 9.2130	8.6077 8.9067	0.3012 0.3063	64.4 64.5	
		Average	.....	....	....	.....	64.5	4.80

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[1] Analyses, unless otherwise noted, were run by C. H. Eldridge and G. B. Dalrymple.

[2] Test piece numbers used are the same as those used in *Bulletins Nos. 4 and 5*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh (1922–1923).

[3] Average figures are obtained from *Bulletin No. 4*, Coal-Mining Investigations, Carnegie Inst of Technology, Pittsburgh (1922).

[4] Analysis furnished by cooperating company.

TABLE I.—(*Continued*)

Designation	Chemical Composition, per cent[1]	Test Piece Number[2]	Area of Test Piece, sq. cm.	Weight, g.		Loss in Weight, g.	Loss per Square Centimeter per 24 Hours in Accelerated Test, mg.	Loss per Square Centimeter per 24 Hours in Long-time Exposure Test, mg.[3]
				Before Immersion	After Immersion			
BRONZES—(*Continued*)								
Rolled zinc phosphor bronze....	Cu 89.8...... Pb 4.6...... Sn 5.6...... Fe trace...... P trace......	49 *a*	13.96	11.1504	10.7887	0.3617	77.6	
		49 *b*	14.07	12.0086	11.6558	0.3528	75.4	
		Average	......	......	......	......	76.5	1.70
Cast lead-zinc bronze..........	Cu 86.34...... Sn 11.24...... Pb 0.83...... Zn 1.60......	73 *a*	13.98	20.5431	20.3666	0.1765	37.9	
		73 *b*	13.96	18.8258	18.6569	0.1689	36.3	
		Average	......	......	......	......	37.1	0.83
Cast lead-bronze...	Cu 74.9...... Pb 14.3...... Sn 10.5......	85 *a*	13.99	19.2448	19.0798	0.1650	35.4	
		85 *b*	14.00	12.8034	12.6320	0.1714	36.6	
		Average	......	......	......	......	36.0	1.26
Cast lead-bronze...	Cu 87.5...... Sn 10.6...... Pb 1.6......	82 *a*	14.01	23.0347	22.8364	0.1983	42.7	
		82 *b*	13.97	21.9898	21.7049	0.1949	41.5	
		Average	......	......	......	......	42.1	2.56
CUPRO-NICKEL								
Rolled cupro-nickel (coin metal).....	Cu 74.60..... Ni 25.40.....	37 *a*	14.04	9.3700	9.0505	0.3195	68.2	
		37 *b*	13.98	9.2146	8.8855	0.3291	70.6	
		Average	......	......	......	......	69.4	7.34
Rolled cupro-nickel	Cu 84.36..... Ni 15.64.....	31 *a*	14.01	9.1140	8.7916	0.3224	69.0	
		31 *b*	14.02	8.8536	8.5368	0.3168	67.8	
		Average	......	......	......	......	68.4	7.44
Cast lead-cupro-nickel...........	Cu 53.57..... Fe 0.61..... Sn 0.56..... Ni 25.30..... Pb 19.58.....	1 *a*	14.00	47.0935	46.8166	0.2769	59.4	
		1 *b*	14.01	44.8712	44.6212	0.2500	53.5	
		Average	......	......	......	......	56.5	4.19
Cast chromium-iron cupro-nickel.....	Cu 42.24..... Ni 35.00..... Fe 9.35..... Cr 11.89..... Si 1.50.....	4 *a*	13.94	45.4226	45.1326	0.2900	62.4	
		4 *b*	13.94	45.8286	45.5154	0.3132	67.4	
		Average	......	......	......	......	64.9	6.58
Cast iron-manganese cupro-nickel.	Cu 71.16..... Ni 19.01..... Mn 2.35..... Fe 7.47.....	112 *a*	13.98	21.2147	20.9373	0.2774	59.5	
		112 *b*	13.94	19.8738	19.5708	0.3030	65.2	
		Average	......	......	......	......	62.4	7.27

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[1] Analyses, unless otherwise noted, were run by C. H. Eldridge and G. B. Dalrymple.

[2] Test piece numbers used are the same as those used in *Bulletins Nos. 4 and 5*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh (1922–1923).

[3] Average figures are obtained from *Bulletin No. 4*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh (1922).

TABLE I.—(*Continued*)

Designation	Chemical Composition, per cent[1]	Test Piece Number[2]	Area of Test Piece, sq. cm.	Weight, g.		Loss in Weight, g.	Loss per Square Centimeter per 24 Hours in Accelerated Test, mg.	Loss per Square Centimeter per 24 Hours in Long-time Exposure Test, mg.[3]
				Before Immersion	After Immersion			
				NICKEL-SILVER				
Rolled nickel silver[4]	Cu 63.78 Zn 17.68 Ni 18.54	13 *a* 13 *b*	14.03 13.99	8.9526 8.8299	8.6017 8.4969	0.3509 0.3330	75.0 71.5	
		Average	......	....	....	......	73.3	7.16
Rolled iron nickel silver	Cu 66.03 Zn 23.99 Ni 9.92 Fe 0.05	43 *a* 43 *b*	14.00 13.85	8.9694 8.9937	8.5844 8.6088	0.3850 0.3849	82.5 83.3	
		Average	......	....	....	......	82.9	7.56
Rolled nickel silver	Cu 52.79 Zn 34.58 Ni 12.63	34 *a* 34 *b*	14.04 14.02	8.5847 9.7871	8.1785 9.3809	0.4062 0.4062	86.9 87.0	
		Average	......	....	....	......	87.0	7.28
Cast silicon nickel silver	Cu 72.3 Ni 16.5 Sn 3.5 Zn 7.4 Pb 0.3 Si trace	10 *a* 10 *b*	13.98 13.94	18.9700 18.6273	18.6756 18.3825	0.2944 0.2448	63.2 52.6	
		Average	......	....	....	......	57.9	6.98
Cast tin-lead nickel silver	Cu 63.52 Ni 12.85 Sn 4.59 Zn 11.55 Pb 7.49	7 *a* 7 *b*	13.98 13.98	25.5543 21.9874	25.2777 21.7511	0.2766 0.2363	59.5 50.8	
		Average	......	....	....	......	55.2	4.24
Cast tin-lead nickel silver	Cu 54.32 Pb 6.30 Sn 2.54 Zn 16.33 Ni 20.51	136 *a* 136 *b*	14.05 13.96	51.0765 51.8583	50.7214 51.4907	0.3551 0.3676	75.8 79.0	
		Average	......	....	....	......	77.4	4.60
				ALUMINUM ALLOYS				
Cast aluminum-silicon alloy	Si 3.90 Al 96.10 (by difference).	88 *a* 88 *b*	13.97 14.01	11.9329 13.3714	11.8573 13.2958	0.0756 0.0756	16.2 16.2	
		Average	......	....	....	......	16.2	2.20
Cast aluminum-manganese alloy	Mn 1.81 Al 98.19 (by difference).	91 *a* 91 *b*	14.00 14.00	13.2254 12.3927	13.1230 12.2919	0.1024 0.1008	22.0 21.6	
		Average	......	....	....	......	21.8	2.23

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[1] Analyses, unless otherwise noted, were run by C. H. Eldridge and G. B. Dalrymple.

[2] Test piece numbers used are the same as those used in *Bulletins Nos. 4 and 5*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh (1922–1923).

[3] Average figures are obtained from *Bulletin No. 4*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh (1922).

[4] Analysis furnished by cooperating company.

TABLE I.—(*Continued*)

Designation	Chemical Composition, per cent[1]	Test Piece Number[2]	Area of Test Piece, sq. cm.	Weight, g.		Loss in Weight, g.	Loss per Square Centimeter per 24 Hours in Accelerated Test, mg.	Loss per Square Centimeter per 24 Hours in Long-time Exposure Test, mg.[3]
				Before Immersion	After Immersion			
		ALUMINUM ALLOYS—(*Continued*)						
Rolled aluminum-manganese alloy	Mn 0.95 Si 0.53 Fe 0.95 Al 97.57 (by difference)	94 *a*	13.92	3.5619	3.4335	0.1284	27.6	
		94 *b*	13.77	3.3678	3.2413	0.1265	27.6	
		Average					27.6	1.76
Rolled aluminum alloy	Cu 3.62 Fe 0.45 Mn 0.46 Si 0.56 Al 94.91 (by difference)	97 *a*	14.03	3.4720	3.3909	0.0811	17.4	
		97 *b*	13.96	3.4674	3.3856	0.0818	17.6	
		Average					17.5	1.73
		RUSTLESS STEELS						
Rolled high chromium steel	Cr 29.5 Mn 0.27 Si 0.55 C low Fe remainder	106 *a*	14.00	9.8948	9.8217	0.0731	15.7	
		106 *b*	13.98	9.9052	9.8355	0.0697	15.0	
		Average					15.4	0.00030
Rolled rustless steel "A"	Ni 23.87 Cr 12.96 Si 3.40 C low Fe remainder	100 *a*	13.98	10.6067	10.5219	0.0848	18.2	
		100 *b*	14.01	9.6819	9.5940	0.0879	18.7	
		Average					18.5	0.00015
Rolled rustless steel "B"	Ni 29.60 Cr 10.73 Si 3.26 C low Fe remainder	103 *a*	13.96	10.2522	10.2251	0.0371	5.8	
		103 *b*	13.97	10.4171	10.3868	0.0303	6.5	
		Average					6.15	0.00074
		MISCELLANEOUS METALS AND ALLOYS						
Rolled ingot iron[4]	Fe 99.9	115 *a*	13.93	7.7169	7.3858	0.3311	71.2	
		115 *b*	13.98	7.9368	7.6026	0.3342	71.9	
		Average					71.6	7.14
Rolled aluminum[4]	Commercially pure aluminum	109 *a*	13.95	3.4326	3.3077	0.1249	26.8	
		109 *b*	13.98	3.4876	3.3562	0.1314	28.2	
		Average					27.5	1.56
Rolled nickel[4]	Ni 99+	121 *a*	13.93	9.8384	9.5956	0.2428	52.2	
		121 *b*	13.74	9.2226	8.9749	0.2477	54.0	
		Average					53.1	0.003

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[3] Average figures are obtained from *Bulletin No. 4*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh (1922).

[4] Analysis furnished by cooperating company.

TABLE I.—(*Continued*)

Designation	Chemical Composition, per cent[1]	Test Piece Number[2]	Area of Test Piece, sq. cm.	Weight, g.		Loss in Weight, g.	Loss per Square Centimeter per 24 Hours in Accelerated Test, mg.	Loss per Square Centimeter per 24 Hours in Long-time Exposure Test, mg.[3]
				Before Immersion	After Immersion			
MISCELLANEOUS METALS AND ALLOYS—(*Continued*)								
Cast aluminum bronze..........	Cu 93.9....... Al 6.1....... (by difference).	76 *a*	13.95	19.7432	19.4351	0.3081	66.4	
		76 *b*	14.05	14.5436	14.2911	0.2525	54.0	
		Average	......	....	....	......	60.2	5.08
Rolled iron-aluminum bronze.	Cu 86.23...... Fe 4.81...... Al 8.96...... (by difference).	52 *a*	13.99	10.2074	9.9225	0.2849	61.1	
		52 *b*	14.01	10.2465	9.9690	0.2775	59.4	
		Average	......	....	....	......	60.3	5.98
Cast copper-lead alloy............	Cu 53.4....... Pb 46.4.......	70 *a*	13.93	44.5236	44.2759	0.2477	53.4	
		70 *b*	13.99	29.7853	29.3419	0.2434	52.2	
		Average	......	....	....	......	52.8	3.87
Rolled monel metal	Ni 65.1....... Cu 30.52...... Fe 4.2.......	40 *a*	13.98	11.4879	11.1633	0.3246	69.7	
		40 *b*	13.98	11.2197	10.9057	0.3140	67.5	
		Average	......	....	....	......	68.6	6.72
Rolled copper-manganese-iron alloy.	Cu 94.81...... Mn 4.52...... Fe 0.67......	61 *a*	14.01	9.3856	9.0581	0.3275	70.1	
		61 *b*	14.02	8.4176	8.0641	0.3535	75.6	
		Average	......	....	....	......	72.85	7.36
Rolled nickel-chromium-iron alloy............	Ni 52.50...... Cr 9.29...... Mn 1.24...... Al 0.20...... Si 0.19...... Fe remainder..	139 *a*	13.97	11.4498	11.3314	0.1184	25.4	
		139 *b*	13.98	12.3374	12.2360	0.1014	21.8	
		Average	......	....	....	......	23.6	7.35
Rolled nichrome...	Ni 57.44...... Cr 9.37...... Si 0.55...... Mn 1.75...... Fe remainder..	118 *a*	14.01	9.9977	9.8676	0.1301	27.9	
		118 *b*	13.98	9.6479	9.5210	0.1269	27.2	
		Average	......	....	....	......	27.55	0.025

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[1] Analyses, unless otherwise noted, were run by C. H. Eldridge and G. B. Dalrymple.

[2] Test piece numbers used are the same as those used in *Bulletins Nos. 4 and 5*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh (1922–1923).

[3] Average figures are obtained from *Bulletin No. 4*, Coal-Mining Investigations, Carnegie Inst. of Technology, Pittsburgh (1922).

Tests were made on 42 metals and alloys in Edna No. 2 mine water, running 12 pieces in series. Table I gives the results obtained in the accelerated electrolytic tests with the comparative figures on the long-time exposure tests. The current throughout was maintained constant at 0.025 ampere, the current density showing slight variations, namely, ±0.01 ampere per sq. dm., due to slight differences in area.

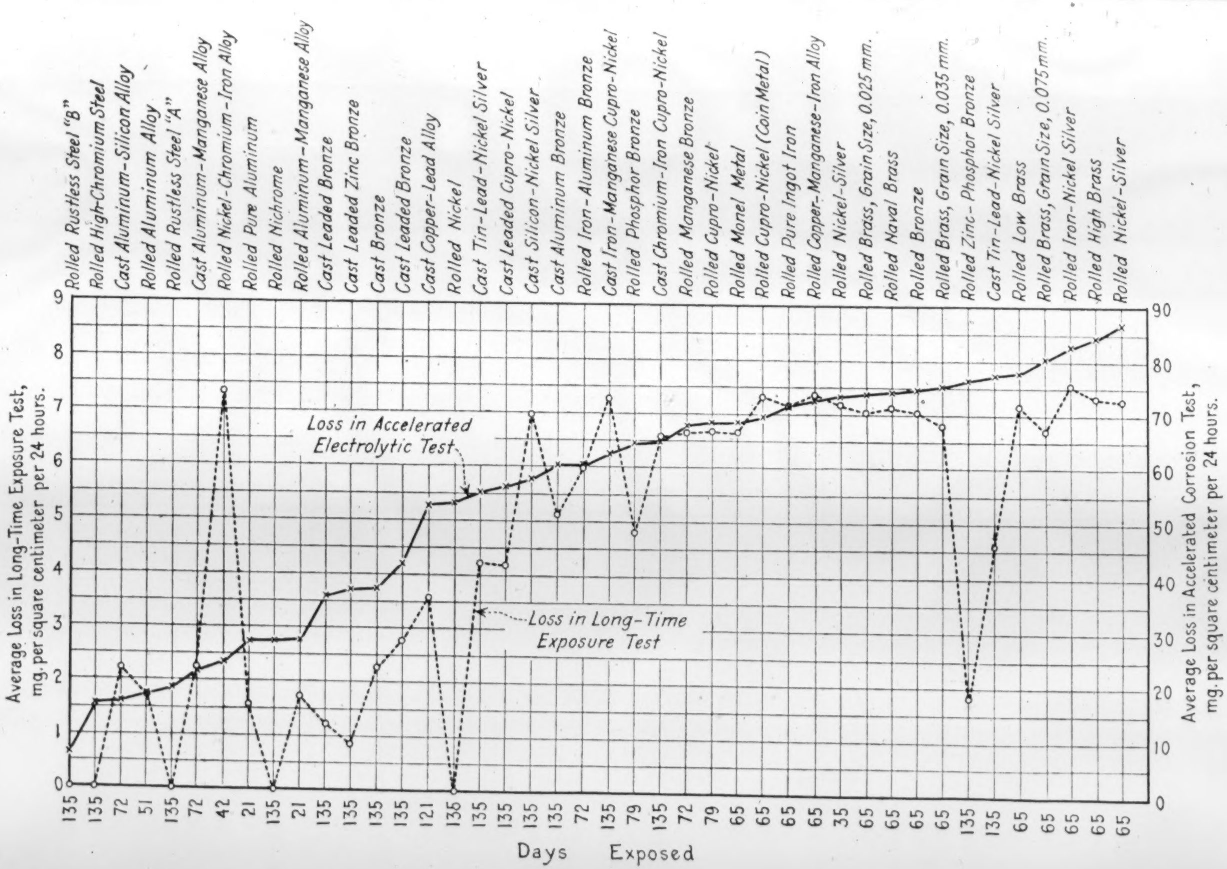

FIG. 3.—Comparison of Corrosion Losses in the Accelerated Electrolytic Test with Losses in the Long-time Immersion Test in Edna No. 2 Mine Water.

The average loss in milligrams per sq. cm. per 24 hours for both the long-time exposure and the accelerated electrolytic tests is plotted in Fig. 3 for each individual alloy. In this way a direct comprehensive comparison can be drawn between the two tests. In plotting the curves, different scales were used for the losses in weight in the long-time exposure test and in the accelerated electrolytic test, so that the two curves of the graph would lie relatively close together.

The figure shows that the curve for the electrolytic test takes roughly the same slope as the one for the long-time exposure. The chief exceptions are found in the case of the following five materials: cast lead-zinc bronze, rolled nickel, rolled zinc phosphor bronze, rolled nickel-iron-chromium alloy, and nichrome. The first three exceptions can be explained on the basis of protective coatings formed; the losses in the long-time exposure test are much smaller than those in the accelerated test. Test pieces of these alloys were exposed 135 days in the mine. After a certain length of time a protecting coating was formed on each piece, with the result that the rate of corrosion was greatly reduced, although neither the rate of corrosion nor reduction of this rate is necessarily a linear function of the time period. In the accelerated electrolytic test, the pieces were all run for the same length of time, namely, 8 hours, while in the long-time test the exposure periods varied from 21 days to 135 days, as shown in Fig. 3. It is, of course, obvious that the exact relation between the time necessary to obtain comparable losses and comparable coatings in both tests is not known on the basis of the present data, and this would necessarily differ for different metals and alloys. Hence, it is not surprising that where protective coatings are formed, as on these three alloys, the results of the two tests should differ considerably. If the accelerated electrolytic tests for these alloys had been run for longer periods, probably the effects of protective coatings would have been made evident in the results, and agreement between the two tests would have been close.

In the rolled nickel-chromium-iron alloy, the greater relative loss in the long-time test is explained by non-homogeneity of the materials, as was shown by microscopic examination. In the test of nichrome, the discrepancy, although marked, is not so great as for the other alloys. It seems quite probable that in the long-time test a protective film may have been formed which did not form in the accelerated test. Such a film, as defined by the authors, would not be visible, and hence would not be noted in the results of the long-time test.

Microscopic examination of the alloys that yielded less loss in the long-time test showed that protective coatings had been formed; no coating was formed on the nickel-chromium-iron alloy.

A fact to be emphasized is that in comparing the observations in the two sets of tests it was noted that the same phenomena occur in the accelerated test as in the long-time exposure test. A few of the similar phenomena observed are the formation of films and coatings, or their failure to form, on materials of the same composition, and the pitting of similar materials. It was even found that with one alloy a gain in weight was obtained in both the accelerated and the long-time tests. The data in Table I show that for each group of alloys the relative order of loss is approximately the same; the rustless steels show the lowest losses, while the brasses in both tests give the highest.

It would naturally be expected that a conversion factor for translating the results of accelerated electrolytic tests into terms of long-time immersion tests should be obtainable, and the results of Table I indicate that the acceleration in the electrolytic test is of the order of 10 times over the ordinary immersion test, depending upon the material, the time period of exposure, and other circumstances.

From the results of these comparative tests, it is evident that the accelerated electrolytic test is of value in examining metals and alloys for relative corrodibility, and, when the various factors affecting corrosion rates are properly accounted for, this test can be readily adopted for quickly determining the life of an alloy. The work reported here is the first systematic attempt to develop an accelerated test and to correlate the results with those obtained in the standard long-time immersion tests. With the few exceptions pointed out previously, the corrosion losses per unit area per day as found in the long-time test and the accelerated electrolytic test for the different metals and alloys are directly comparable. The general nature of the corrosion in both tests is the same, *i. e.*, as to coatings formed, pitting, and other surface features which are ordinarily observed.

The possibilities of this accelerated test are definitely shown by the fact that the average corrosion losses for the different groups of metals and alloys take about the same order as they do in the long-time exposure tests. It is apparent that the accelerated electrolytic test shows considerable promise.

In examining the general corrosion results for the different groups of metals and alloys, as was done in the long-time immersion tests,[1] the following observations were made:

The alloys of the brass and bronze types were corroded very uniformly, the latter to a much smaller extent than the brasses. Evidently copper-tin alloys of the bronze type are preferable to copper-zinc alloys for use in mine waters.

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[1] W. A. Selvig and G. M. Enos, *Loc. cit.*

The cupro-nickel alloys are corroded uniformly and show about the same amount of corrosion as the brasses.

The nickel-silver alloys were badly corroded, but here again the corrosion was uniform. The aluminum alloys show much smaller weight losses than the brasses, bronzes, and nickel-silvers, but have a tendency to pit quite badly, thus precluding their use in mine water.

The rolled rustless steels show the smallest amount of corrosion and seem the most suitable alloys for use in mine water. In this class are included two chromium-nickel-silicon steels (test specimens 100*a* and 100*b* and 103*a* and 103*b*) and a high-chromium steel (test specimens 106*a* and 106*b*).

The conclusions reached as to the behavior of the various metals and alloys in the accelerated electrolytic test using acid mine water as the electrolyte are the same as those reached after carrying out the long-time immersion tests,[1] with the exception of the ranking of nichrome, which must be placed lower on the basis of the accelerated test; and note should be made that the high-silicon cast irons were not included in the accelerated test.

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[1] W. A. Selvig and G. M. Enos, *Loc. cit.*

DISCUSSION ON CORROSION TESTS OF METALS

Mr. F. N. Speller[1] (*presented in written form*).—Most of the types of apparatus referred to in the paper by Mr. Rawdon and his associates have application to certain sets of conditions. The authors should have stated emphatically in the negative that there is no "all around test." **Mr. Speller.**

The hit-or-miss tests which have been developed in the attempt to determine the physical properties of metals should be avoided in the development of a system of testing the durability of metals under corrosion. Accelerated tests should have a scientific and practical connection with service tests, or tests made under service conditions. To start with, more attention might be paid to the principles which should govern corrosion testing and less to the mechanical details of the various kinds of tests proposed.

Before attempting to adopt a system of testing, it would seem to be useful to first list the established facts and factors influencing corrosion, which should be followed by an official statement of the theory which is most generally agreed upon in explanation of the facts.

With this basis it will be seen that corrosion may be classified into various types, in each of which a few factors control and bear a more or less fixed ratio to one another. For instance we may classify all corrosion under the following groups:

1. Atmospheric Corrosion;
2. Underwater Corrosion (continuous immersion);
3. Alternate Wet and Dry (water line corrosion);
4. Soil Corrosion (*a*) *per se* or
   (*b*) With Electrolysis;
5. Chemical Corrosion.

These may be subdivided still further into groups in which a still smaller number of controlling factors are involved, or in which these factors bear a different relation to each other with respect to their relative importance. For example, underwater corrosion may be divided (as R. E. Wilson has pointed out) into corrosion in alkaline, neutral and acid water in each of which different factors predominate.

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[1] Metallurgical Engineer, National Tube Co., Pittsburgh, Pa.

Mr. Speller. A general specification could now be written stating the principles of corrosion testing and the permissible variations in important factors for each type of corrosion, which should govern all valid tests of the accelerated type in each class. For example, oxygen content, velocity and temperature value in immersion tests are accelerating factors but may be varied between certain limits only.

Tests in actual service naturally involve all the factors and the variations usually found, but obviously the results of tests from one type of service cannot be applied to other types although this error is still the basis of some opinions.

Accelerated tests may be divided into those adapted for investigation of the effect of corrosion factors, involving the fundamental reactions; and accelerated tests to destruction, which include also important secondary factors. An accelerated test which is valid for one class of corrosion might be misleading in another class. The electrolytic test used by Anderson and Enos, for instance, may bear an approximate relation to service tests in acid mine water, but is probably limited to this case. With respect to the time factor, service tests in mine water are, as a matter of fact, shorter than most accelerated tests should be under less strenuous conditions so that an accelerated test may not be needed in such media. Having waited so long for a rational and reliable system of corrosion testing, let us get started right.

The methods of testing recommended in the report of Committee B-3 on Corrosion of Non-Ferrous Metals and Alloys show a very thorough analysis of opinions on this subject. The recommended systematic study of the tests proposed cannot fail to bring out useful information. It should be remembered that this procedure has been worked out from the point of view of "Chemical Corrosion" and will probably have to be modified in important details in dealing with natural corrosion (atmospheric, underwater and soil corrosion) which includes by far the greatest loss of metal. The conclusions drawn from these tests should be limited to the solutions used and to a general comparison of the methods employed. In making the aërated immersion tests it would seem that the air should be added through a porous crucible as suggested in the report of Mr. Rawdon's committee. The writer prefers to express the results in "average inches penetration per year" which is a figure of practical significance. The depth of pitting should be measured independently and need only give the "depth of deepest pit" or "depth of the five deepest pits."

A rapid and fairly reliable method of testing is much needed in the development of alloys resistant to corrosion, without which much

Mr. Speller.

time and effort will be wasted. The corrosion problem has become one of the most vital problems with which engineers have to deal. The work done by Committee A-5 on Corrosion of Iron and Steel and by Committee B-3 will have a powerful influence for better or for worse. It would seem, therefore, that these committees should work together more closely. Perhaps the work might be consolidated into one committee with advantage.

Mr. Whitman.

MR. W. G. WHITMAN[1] (*presented in written form*).—The comparison of electrolytically accelerated tests with long-time exposure tests, given in Table I of the paper by Anderson and Enos, shows a decided lack of agreement between the results of the two methods. For example, the maximum rate of corrosion in the accelerated test is only fourteen times greater than the minimum, while in the long-time exposure the maximum is fifty-thousand times the minimum. The accelerated tests, therefore, show much less differentiation between the metals than is observed in the exposure tests.

The authors admit that the comparison between the two tests is poor in the cases of five of their specimens. From an inspection of the table it would also seem reasonable to include the three rustless steels and the cast lead-bronze in this category, making a total of nine exceptions in forty-two examples. It is important to note that eight of these nine exceptions are among the eleven specimens showing lowest corrosion (below 2 mg. per sq. cm. per 24 hours in the long-time tests), the other three samples in the group of eleven being aluminum alloys which should have low rates anyway, as explained below). The accelerated test, therefore, fails where it is most needed, that is, in sharply differentiating the more resistant metals.

It is interesting to compare the results of the accelerated tests first with those of the long-time test and second with the results which would be predicted from Faraday's law. The average current density employed (0.18 amperes per sq. dcm.) corresponds to 1.61 milliequivalents per sq. cm. per 24 hours. This would be equivalent to 51.2 mg. of copper, 52.6 mg. of zinc, 14.5 mg. of aluminum, etc., dissolved from the anode if Faraday's law could be applied directly. In the actual test, the amount dissolved may be somewhat greater because of the so-called "chemical" attack by the solution or by the actual flaking off of metal, or it may be less if the metal is highly resistant to anodic corrosion. The following table is drawn up from the authors' data, using their own classification of the samples.

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[1] Assistant Director, Research Laboratory of Applied Chemistry, Massachusetts Institute of Technology.

Mr. Whitman.

	NUMBER OF SAMPLES	RATIO: ACCELERATED TEST / LONG-TIME TEST		RATIO: ACCELERATED TEST / THEORETICAL (FARADAY'S LAW)	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
Brasses.......	7	10.2	12.0	1.31	1.62
Bronzes.......	7	10.6	45.0	0.70	1.49
Cupro-Nickel..	5	8.6	13.5	1.15	1.42
Nickel-Silver...	6	8.3	16.8	1.09	1.72
Aluminum alloys	4	7.4	15.7	1.12	1.90
Rustless steels.	3	8300	120 000	0.14	0.41
Miscellaneous..	10	3.2	17 700	0.50	1.90
Total.....	42	3.2	120 000	0.14	1.90

It is readily seen that the results of the accelerated tests correspond much more closely to Faraday's law than they do to the results of the long-time test. Thus, in the Faraday law comparison, the minimum figure is obtained with a rustless steel which gave 14 per cent of the theoretical corrosion, while the maximum is with rolled aluminum, which corroded about twice as fast as the theoretical. On the other hand, the comparison of the accelerated with the long-time test varies almost forty-thousand fold. This accelerated test for predicting service corrosion, particularly where applied to the more resistant metals, seems therefore to be of very questionable significance.

The authors assume that the proper protective films would be built up and that the results would therefore be much more significant if their accelerated test were continued for a longer period of time. This assumption seems questionable, since the result of making the test piece completely anodic by electrolytic methods is to radically change conditions from those of corrosion in service where the cathode reaction can also occur on the corroding sample.

Mr. Rawdon.

MR. H. S. RAWDON.—I should like to say just a few words concerning some work we are doing at the Bureau and plan to present a little more fully later on. Suppose you take a piece of metal and polish it and then make a thin metal shield and cut out any sort of design you want and put the two in contact, with the metal shield facing out and expose it to ultra-violet light for several hours; then take your polished metal out. Ordinarily you won't see that anything has happened to the surface of it. If you cool the specimen and blow your breath on it, the pattern revealed corresponding in all details to the design cut in the shield will be very prominent and very striking. We do not yet know just what that means, but it is evident that the short wave lengths of the ultra-violet rays do have some effect on the surface of the metal and it has some bearing on the corrodibility of that metal. It seems as if there is something in the nature of an "oily" film formed on the exposed portion, because the condensed film of moisture coalesces into large drops on the exposed portion much faster than it does on the unexposed portion. Under the microscope you can see the drops of moisture as they coalesce. They are much larger there than on the unexposed part, and this would seem to depend upon the nature of the surface film that was formed under the influence of the short-wave radiation. It is a very striking, rather mysterious phenomenon, but I believe it has some significance in the corrodibility of metals under atmospheric conditions. **Mr. Rawdon.**

Mr. Finkeldey.

MR. W. H. FINKELDEY.—I have here several specimens of galvanized sheet iron, carring light and heavy coatings of zinc, which have been subjected to the simulated atmospheric test. Several samples of each of these galvanized sheets were placed under test and the specimens removed from the tank at various times to show the changes in the appearance of the zinc coating. You will note that after one or two cycles the sheets lose their metallic luster and become coated with a light gray protective film. The spangles gradually disappear as the specimen is exposed to additional cycles and finally dark colored spots begin to appear over the surface of the sheet. After a few more cycles the sheet becomes dark colored over its entire surface. The change in color from light to dark gray is due to the uncovering of the iron-zinc alloy layer overlying the iron base. After undergoing several more cycles this alloy layer is removed and the exposed iron base will start rusting. The appearance of the coating on these specimens during the various stages of testing resembles very closely the appearance of the coating on ordinary galvanized iron as it fails in the atmosphere and this similarity is most particularly marked in the appearance of the dark colored alloy layers.

We have repeatedly observed that a greater number of cycles are required to show the first spots of dark colored alloy layer in the case of the heavily coated galvanized iron than are necessary in the case of the light coated sheets. This same difference in the performance of the two kinds of galvanized iron can be observed, when they are exposed in the atmosphere. In other words, the length of time required to show up dark spots on the galvanized sheets when exposed in an ordinary atmosphere is a good indication of the amount of relatively pure zinc coating overlying the alloy layer and is a useful forecast of the probable life of the protective coating.

The relative rates of corrosion, in the atmosphere, of the pure zinc layer and the iron-zinc alloy layer are not definitely known. This is a very important point and should receive the careful attention of anyone investigating protective zinc coatings.

Mr. Finkeldey. The development of this test was practically forced upon us because of the unreliable results which we secured with the salt-spray test. Our preliminary investigations indicated that moisture, heat and the concentration of gases known to exist in the atmosphere of some of our industrial centers were the most important of all the atmospheric effects. It is very important, however, that the washing action of rain be imitated to remove corrosion products and that the specimens be given a chance to dry thoroughly to renew their protective films. After a few preliminary experiments we arbitrarily selected gas concentrations of 5 parts of CO_2, 1 part of SO_2 to 100 parts of air because these produced failure of the coating in a reasonable length of time.

The size of the test specimen is important. It is dangerous to draw conclusions from the corrosion tests made on specimens a few inches long and an inch or so wide because all the variations that occur in a galvanized coating will not be found on such a small sized sample. Our regular test specimen is 2 ft. by 18 in.; full size galvanized sheets would be even more desirable.

Although we have not yet had time to complete accelerated tests on our large collection of various kinds of galvanized iron samples and correlate the results obtained with those secured by exposure to the atmosphere, we thought it advisable to present a description of our test procedure to stimulate interest in this method of testing. If other investigators experiment with this type of test, making such variations in the procedure as seem advisable to them, possibly their results will show that several advantageous changes can be made in our present method of conducting the test. We will be glad to send to anyone interested a description of this test, including working drawings for the construction of the test tank.

Mr. Cushman. MR. A. S. CUSHMAN.[1]—I should like to ask whether any attempts have been made to test the test? I mean will it distinguish material that has been in service and given successful service a number of years as against material that has failed? What I fear about this type of test is that it develops into nothing more than a stripping test; that is, it distinguishes between a material that has a heavy coating per square foot and another that has a slightly lighter coating per square foot, but there is no evidence that has yet been presented that I know of to show that this test would serve as a useful guide in distingusihing between different types of galvanized sheets so far as real service is concerned. It would appear that the authors of the paper have rather focused their attention upon, we will say, material

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[1] Consulting Metallurgist, Washington, D. C.

Mr. Cushman.

that is exposed as it is in a roof or in siding, but I submit that the bulk of galvanized sheet metal does not go into that kind of service at all. A great many culverts are used all over the world and they are not subjected to the same conditions at all. I am not trying to knock this test. I think good will come out of all these attempts and we will learn something. I am simply questioning whether there is not a danger that people who have not studied corrosion problems very much will want to insist that an acceleration test like this be made a matter of specification before the test has justified itself. Nothing is more desirable than an accelerated test that will tell us the truth. We all want it, and we have been after it for years, but no such test should be accepted by engineers as a criterion until the test has been tested, with reference to known long life of service of different kinds of material of equal weight of coating. We ought to know very certainly that any proposed test is telling us the truth and not misleading us.

Mr. Finkeldey.

MR. FINKELDEY.—I heartily agree with what Mr. Cushman has said, that there is danger of using this test to determine the suitability of material for service conditions which are not at all related to atmospheric corrosion. However, there is a possibility of as much damage being done by purchasing galvanized sheets without paying any attention at all to the character of the zinc coatings. Perhaps a little misplaced effort on the part of a few investigators will take us no further afield than being content to remain in ignorance of some of the most important facts about protective zinc coatings, which unfortunately is the attitude of many users of galvanized products.

Mr. Gibboney.

MR. J. H. GIBBONEY[1] (*Chairman, Committee A-5*).—I am sure that we have been impressed by the great amount of work that has been done within the past two or three years in developing methods of corrosion tests. Committee A-5 has an active sub-committee studying this matter which has reported considerable progress from year to year, and now we seem to be ready to make accelerated tests which bid fair to give a reliable measure for comparing the service value of galvanized products. While accelerated tests have a very definite value for quick comparative determinations, we cannot expect to rely on such tests for specification use until the tests have been proved reliable by comparing the findings with actual service results. Committee A-5 now proposes to conduct parallel accelerated and actual service tests on galvanized products made by the several well recognized processes, and while such work will require years of study for completion, it is certainly well worth doing. We think that our program as outlined in the report of Committee A-5 is a constructive be-

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[1] Chemist, Norfolk and Western Railway Co., Roanoke, Va.

Mr. Gibboney. ginning in this very important field of research and it is deserving of the heartiest support of our members. If we can finance this comprehensive undertaking we are confident that within a few years we will have information on the service value of galvanizing coatings quite as valuable as the results that we have just about completed relating to the rust resistance of the base metals.

Mr. Gillett. MR. H. W. GILLETT.[1]—I should like to interject another note of optimism in the discussion in regard to the accelerated electrolytic test. It has been severely criticized on account of the lack of correlation between it and the immersion test, but we should add to our study on accelerated electrolytic tests the study of polarization voltages or other suitable electrical methods to show where the film forms on metals and in different solutions. If that is done in conjunction with the electrolytic test and the electrolytic test is properly modified to take that into consideration, changing the current density in the light of this information, the chances of getting correlation after we know more about how to conduct the electrolytic test for any particular type of material, will be very much better than they appear to be at the present time.

Mr. Carson. MR. H. Y. CARSON.[2]—I have read these two papers and also listened to the discussion with a great deal of interest. Many of the points which are here discussed were recommended for study by the Committee on Corrosion of Metals of the American Foundrymen's Association about three years ago. As I am a member of this committee, it is with a great deal of pleasure that I see set down here some of the points concerning which we were anxious to obtain information at that time. There are still one or two features about accelerated corrosion testing which I think ought to be borne in mind. One is that we must always analyze our practical situation and then apply the accelerated test to that practical situation as nearly as we can do so. For instance, in studying underground corrosion of metals, we find there are at least three conditions obtaining which we should simulate in any accelerated test: first, we have rain water falling on the ground and percolating through the soil, taking up the salts, some of which are acid and some of which are alkaline. The water thus carries that solution to the surface of the metal in a more or less concentrated state. Second, there is a drying out or complete oxidizing effect, and, third, there is a total flushing action under most conditions. In arranging a salt spray test or as it should better be called a "spray test," we have found in our A. F. A. Committee tests that we can get an

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[1] Chief, Division of Metallurgy, U. S. Bureau of Standards.

[2] Research Engineer, American Cast Iron Pipe Co., Birmingham, Ala.

Mr. Carson.

alteration or variation involving these above-mentioned three conditions by using various salt solutions and allowing the specimens to dry, then using distilled water as an alternate spray. It is really surprising, however, to see that distilled water will react with the metals in some cases even more readily than the salt solutions do. I think another point is that whenever any corrosion situation is to be examined there should be a parallel examination between the accelerated test and the actual service condition, but it will take years to build up useful data this way. In our A. F. A report in 1923 we brought that feature out very prominently by suggesting that the present long-time tests being run by the Bureau of Standards and Committee A-5 be paralleled with accelerated tests; that, of course, will take 15 or 20 years before our accelerated tests begin to resolve themselves into their various useful groups. Mr. Speller, in his written discussion, mentioned five groups of conditions, but I think his division could readily be extended or expanded to ten or fifteen groups. It might prove rather complicated, however, to go into these various conditions or groups of corrosion and therefore we have found it more simple for the present to assume only two general groups of corrosion which we place this way: first, that condition where the products of corrosion are retained on the metal, and, second, where the products of corrosion are constantly removed from the surfaces of the metal. Mr. Whitman mentioned the protective film idea. We, too, have done some interesting work recently on the effect of certain alkaline cement coatings which form a chemical film on ferrous metals; and it is rather interesting to theorize, as you might say, on why a cement film or coating protects a metal like iron. The removal of the hydrogen ion from the water as it passes through the film of cement, which by the way need be only thick enough to remain mechanically in place, causes deactivated water to be held adjacent to the surface of the iron for an indefinite period of time. Iron which has been protected for a number of years with cement may have the cement removed from its surface and you will see a surface film of neutralized water run right off of the metal, but after that metal has been exposed to the air so that carbon dioxide, among other acids as well as oxygen, comes in contact with it, corrosion will start within a very short time at the same point at which the cement has prevented any oxidation over a period of 40 or 50 years. I think it is very gratifying to know that these papers have brought out so many points of progress and we hope that as a next step in this work action will be taken to parallel this excellent short-time corrosion research with the long-time corrosion tests which are now running and which the chairman of Committee A-5 has already proposed to carry out in the future.

Mr. Lynch.

MR. T. D. LYNCH.[1]—When these papers came out I handed them over to one of our chmiecal engineers and he presented a thought that I have not heard expressed at this meeting, which may be of interest to the members of the convention as well as to the committee itself. It is this: he told me that zinc with an analysis of 99.959 per cent pure zinc, the rest lead and manganese, can be immersed in a 10-per-cent solution of sulfuric acid for 40 hours and lose not to exceed 5 per cent of the metal. He also stated that zinc having 99.8 per cent of zinc, 0.19 per cent lead, 0.01 per cent iron would dissolve readily. I am wondering whether it is not that thin coating dissolved or combined with the iron that has given away quickly, whereas an extra amount of coating gives you the resistance to the atmosphere, or the conditions which in galvanizing offer resistance. I am simply offering that for what it is worth to the committee and the members of the convention to take into consideration and study.

Mr. Breyer.

MR. F. G. BREYER.[2]—That thought gives me occasion to mention a thing that I think the committee on corrosion will be very much interested in. We have made some spectroscopically pure zinc; I do not know whether the Bureau has checked up our finding as yet, but we have tested it very carefully, and as far as we can determine it is absolutely spectroscopically pure. We make high-grade metal, running 99.95 per cent zinc, which will dissolve more slowly than common metal, which runs 99 or 98.5 per cent. Then we make c. p. metal 99.993 per cent zinc that dissolves faster than the high-grade metal. When, however, we went from 99.99 up to spectroscopically pure material, the latter was almost insoluble in dilute sulfuric acid. This seems to me a very interesting sidelight on the theory of corrosion.

Mr. Gibboney.

MR. GIBBONEY.—While the information regarding the greater insolubility of this very high purity zinc is of interest, we are wondering why the producers of galvanized metal have apparently made so little progress in keeping their galvanizing bath free from metal contamination. It is quite generally recognized that iron contamination very seriously increases the solubility of zinc coatings, but until we can perfect the practice to remove the liability of such contamination there will be little or nothing gained in using such high purity zinc. Unquestionably we want a purer zinc in the galvanizing coatings, and we think that the producers of galvanized products should strive to develop their methods of galvanizing so as to make use of this higher purity metal.

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[1] Manager, Materials and Process Engineering Department, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

[2] Chief, Research Division, New Jersey Zinc Co., Palmerton, Pa.

Mr. Speller.

MR. SPELLER.—There are two reasons I know of why we do not use c. p. zinc. I might say three, the third would be the cost, but the cost of course is no consideration here. The first reason is that under water you do not find much difference, if any, in the rate of corrosion between pure zinc and zinc that carries about 2 per cent of impurities. I cannot speak so much from the standpoint of atmospheric corrosion. In acid solutions there is a wide difference, but a little cadmium, lead and iron in zinc does not have much influence on corrosion rate in most natural water; in fact, we have found it to stand up somewhat better in laboratory tests. The second reason is that as soon as you put this zinc in the bath in the hot galvanizing process, it immediately becomes contaminated with iron so that it is impracticable to maintain this standard of quality by the hot process.

Mr. Outerbridge.

MR. A. E. OUTERBRIDGE, JR.[1]—I have been most interested in these discussions, especially regarding the accelerated tests and the long-time tests. I have noticed that a great deal of attention has been paid to the effect of sunlight, ultra-violet light, heat, etc., but I am rather surprised that the question of low temperature does not seem to have entered into the discussion. All metallurgists are familiar with that peculiar condition known as "tin disease." In the celebrated case of a famous organ in Russia where the pipes made of tin disintegrated after some weeks of extremely low temperature by forming little pits (subsequently called tin disease) the pits continued to grow and grow long after the low temperature had passed away. At one time tin-coated plates were used for roofing purposes. In Russia they could not be used at all on account of that tin disease. Whether any similar cause of disintegration affects zinc, I do not know, but I merely recall this instance.

Another point is, I should like to know whether careful tests have been made with respect to the corrodibility of iron with zinc coatings made by modern methods as compared with the older methods. A great many years ago, in 1874, I had occasion to make some experiments along these lines in which inter-alia gold leaf was placed upon plates of different metals, such as iron, steel, copper, etc., pressed so that (with atmospheric pressure of 15 lb. per sq. in.) the gold leaf made seemingly a perfect coating; then the same weight of gold was placed upon metal sheets of the same size by galvanic action, *i. e.*, electroplated. The beaten gold leaf coatings, as might be expected, were porous and, when subjected to tests, they did not thoroughly protect the surface of the metal exposed to oxidizing influences. Various acids being placed upon the surface of the gold had no effect

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[1] Metallurgist, William Sellers and Co., Inc., Philadelphia, Pa.

Mr. Outerbridge. upon the gold but had an effect upon the iron or the other metals underneath. It was the same with vapors, but the films of gold deposited by the galvanic battery stood all those tests; they were not porous. To carry on these investigations still further, I found that by plating a certain weight of gold upon a certain area of copper foil on one side only and then floating the plated copper foil upon a bath of iron perchloride, the whole of the copper was dissolved without making any gas to puncture the gold film. The result was that the gold film floated upon the surface of the liquid and by putting a glass plate underneath, it could be floated off onto distilled water and then fixed upon glass and examined under the microscope by transmitted and reflected light.

Perfectly continuous transparent gold films, vastly thinner than the thinnest beaten gold leaf, were obtained in this manner, the molecular structure of electroplated gold films and of all other metal films is absolutely continuous when examined under highest magnification and the query arises whether the modern methods of galvanizing give as efficient covering to iron or steel as did the older methods of coating, due to possible differences in molecular structure of the coating metal.

Messrs. Anderson and Enos. MESSRS. ROBERT J. ANDERSON AND GEORGE M. ENOS (*Authors' closure by letter*).—The writers have read with interest the discussion of their paper by Mr. Whitman and wish to state at the outset that it is obvious that the agreement between the results of the accelerated electrolytic test and the long-time immersion test is not so close as is desired. At the same time, the writers feel that the agreement is certainly sufficiently close to be quite significant when consideration is taken of the fact that many of the variable factors which determine corrosion rates can be only partially controlled. In the very nature of the case, some sacrifice in accuracy is to be expected, that is, in securing close agreement in the test data, if the time period of testing is to be shortened. This is what the writers propose by the accelerated test, namely, shortening of the time period of exposure. The writers feel that even if the accelerated electrolytic test gave only approximate agreement with the long-time immersion test (and they are not willing to concede that it gives nothing better, on the basis of the data presented), it would still be a useful test. However, so far as the writers can determine, the agreement is much better than approximate, and certainly surprisingly good.

It might very well have been emphasized in the paper that the composition of the mine water used for the accelerated electrolytic tests was not exactly the same as that used for the long-time immer-

Messrs. Anderson and Enos.

sion tests. Detailed analyses of the waters used in the former tests have been given in another paper by the writers and J. R. Adams,[1] and in the latter tests by Selvig and one of the writers.[2] The writers did not stress this particular point since the data given were in sufficiently close agreement to demonstrate the possibilities of the new test, but since the composition of the mine water used for the accelerated electrolytic tests was only approximately the same as that used in the long-time immersion tests, it is not surprising that there is not closer agreement in the results because of this factor alone. It will be conceded that small changes in composition of a corroding medium may be accompanied by appreciable differences in corrosion rates, all other conditions being the same.

The lack of agreement in the case of the five materials referred to was fully explained on the basis of evidence obtained by microscopic examination. It is difficult to make comparison of corrosion losses among the more resistant materials, particularly the rustless steels, since the losses for these are not of the same order of magnitude as for the other materials; for example in the long-time tests on the rustless steels there are decimals and three zeros before a significant figure appears.

In applying Faraday's law to the corrosion of metals and alloys, great care must be used, since it can be applied only indirectly and then with certain limitations. If the corroded sample be entirely freed of corrosion products and the exact weight loss be known, or if an exact analysis be made of the corrosion product, Faraday's law may be applied in certain cases. Thus, in the case of substantially pure metals in certain electrolytes, the theoretical and actual values found will agree closely. In the case of alloys, the agreement will be good, provided that one or more of the components or phases is readily dissolvable by the corroding medium. So little is known about the exact mechanism of corrosion and about the mathematical relationships of the determining factors in the corrosion rate, that it would seem as though calculations such as have been made by Mr. Whitman can have little value. Certainly, it cannot be assumed that an alloy will go into solution at the same rate at which its constituents would be deposited from solution when a current is passed through the cell. The composition of the alloy will very markedly affect the rate of solution.

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[1] R. J. Anderson, G. M. Enos, and J. R. Adams, "Accelerated Corrosion Testing of Metals and Alloys in Acid Mine Water," *Bulletin No. 6*, Coal-Mining Investigations Series, Carnegie Inst. of Technology, 1923.

[2] W. A. Selvig, and G. M. Enos, "Corrosion Tests on Metals and Alloys in Acid Mine Waters from Coal Mines," ***Bulletin** No. 4*, Coal-Mining Investigations Series, Carnegie Inst. of Technology, 1922.

Messrs. Anderson and Enos.

At the time when this paper was prepared, a sufficient number of accelerated electrolytic tests had not been made to determine precisely what would be the effect of film and coating formation upon the acceleration or retardation of the rate of corrosion. Microscopic examination showed that in practically every case the coatings built up in the accelerated test were similar in nature to those formed in the long-time test, but not so thick. Since the paper was prepared, experiments have been carried out by one of the writers (Anderson), which, while not sufficiently numerous to be definitely conclusive, do indicate that when the time period of exposure is suitably increased the agreement between accelerated and long-time results is better than when the eight-hour run is employed. Thus, where alloys form thick coatings which retard the corrosion rate in the long-time test, increasing the time period of exposure in the accelerated test permits the coating formed there to build up and also retard the corrosion rate. Obviously, the number of experiments necessary to determine the conditions of balance, as affected by coating formation, for only one alloy and one corroding medium, is large.

In conclusion, the writers wish to thank Mr. Whitman for his discussion and comments and also to state that the application of this accelerated test need not be hindered because of the lack of many comparative data with long-time immersion tests. At the same time, it will be highly desirable to secure as many comparative data as possible for different metals and alloys in different corroding media.

INFLUENCE OF AGGREGATES UPON SHRINKAGE OF MORTAR AND CONCRETE

BY CLOYD M. CHAPMAN[1]

The subject of this paper is one which has received little attention from the many investigators who are delving into the "whys and wherefores" of good and durable concrete. Little, if anything, seems to have been done toward ascertaining whether concretes and mortars made with aggregates of different kinds of rock behave differently in the matter of contraction on hardening. Literature on this particular subject appears to be entirely lacking, although the data presented herewith indicate that it is one which may be very important under some circumstances. Cracks in concrete construction are seldom desirable—they are often most undesirable. One of the many causes of cracks is the tendency of concrete and cement mortar to shrink as it hardens. Much cracking is undoubtedly due to this cause, perhaps more than has generally been supposed.

At least one case of very serious cracking was found to be due to the use of an aggregate which caused the concrete to shrink on hardening to a very unusual degree. A few years ago a mid-eastern manufacturing company built to its factory building an extension of the brick-wall, steel-column, steel beam-and-girder, concrete-floor type of construction. The concrete in the slab was 1 part cement, 2 parts bank sand and 4 parts crushed stone. The wearing course, which was 1 in. thick, was 1 part cement to 2 parts quarry screenings, which were run-of-crusher passing a $\frac{1}{4}$-in. rotary screen. This rock is geologically known as Pottsville conglomerate (Carboniferous System) and is a sedimentary rock consisting of granitic or syenitic fragments cemented by silica. The concrete was mixed in a batch mixer, wheeled to place in barrows and the top course applied immediately after the main slab had been leveled off and screeded. After setting up, the floors were covered with sawdust and kept damp for several days. The foreman was an experienced concrete man who had previously successfully handled many concrete jobs for the contractor.

The floors are said to have looked unusually well at the time of their completion; the surface was even and smooth and everything appeared to be satisfactory. They had not been down many weeks, however, before cracks began to appear on their surface, over the beams and girders, and along the walls, and across the slabs from beam to beam, between the girders. These cracks increased rapidly, both in number and in size. In places the edges of the slabs curled up at the cracks, and in a few cases the wearing surface came loose from the main slab and curled up at the crack. Such cases of loosening were rare, however, as the wearing course clung tenaciously to the main slab in all but a very few spots. These cracks, while very prominent on the upper surface, were rarely to be seen on the under surface of the slab. They extended only through the wearing course.

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[1] Dwight P. Robinson and Co., New York City.

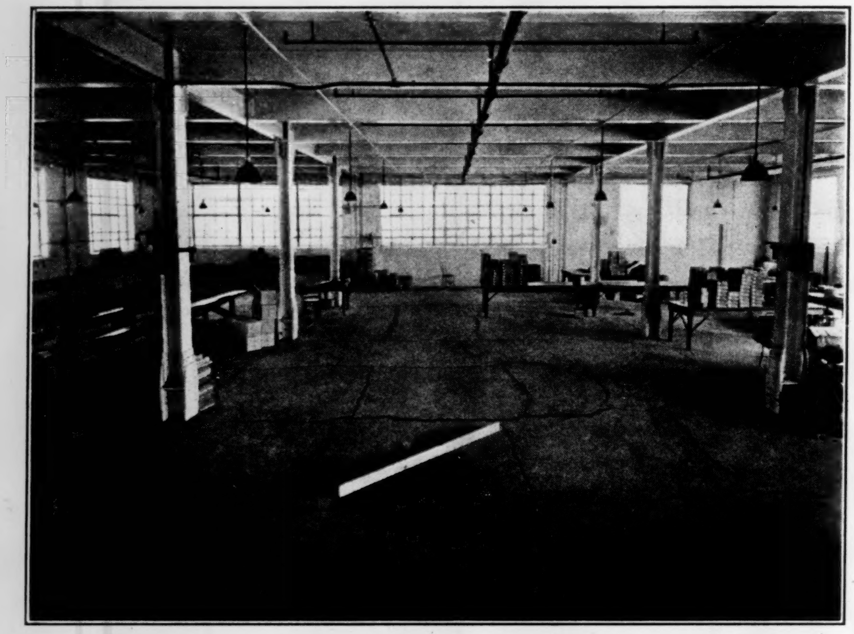

FIG. 1.—Curling Up of Concrete Floor into Large "Saucers." Note pocketknife under straight edge.

As the cracking progressed, the floor became divided up into sections of rectangles some 4 to 6 ft. on a side and these sections curled up at their edges so that each rectangle became a slightly concave plate or saucer. The action was strikingly similar to the curling up of little cakes of clay or silt when a mud puddle dries out in the summer. Looking across this floor, when the light was best suited, one could see the large saucers curled as uniformly as could be imagined. Fig. 1 is a view of a portion of one of the floors. To make the curling up more apparent to the eye, a straight-edged board has been placed across the floor section in the foreground and a pocket knife placed under the center of the straight edge to draw attention to the concave surface. The photograph also shows the marked uniformity of the pattern made by the cracks. There is a crack over each beam and each girder and two or three cracks across each slab extending from beam to beam. There are other evidences of the curling up of the floor slab. In some cases the slab in curling up has left a portion behind in its original position. In such cases the amount of the movement may be accurately measured.

In several corners of the building where the floor was cast against two brick walls, and also at columns where steel I-beams pass through the floors, the concrete slab in working upward has left behind broken-off portions, which still retain their original position as is evidenced by the unbroken paint film around them. Such a case is illustrated in Fig. 2, which shows the under side of the slab at a corner of the building. Note that a triangular piece is left in its original position in the corner, while the remainder of the slab has curled up and is not resting on the steel channels from the one arrow around to the other arrow. The upward movement of the slab here was about $\frac{5}{16}$ in. In these and other ways evidence might be accummulated to show that practically every panel of every reinforced floor slab in this building had cracked on its upper surface and curled upward at its edges, and very few of these cracks are to be seen on the under side of the slab.

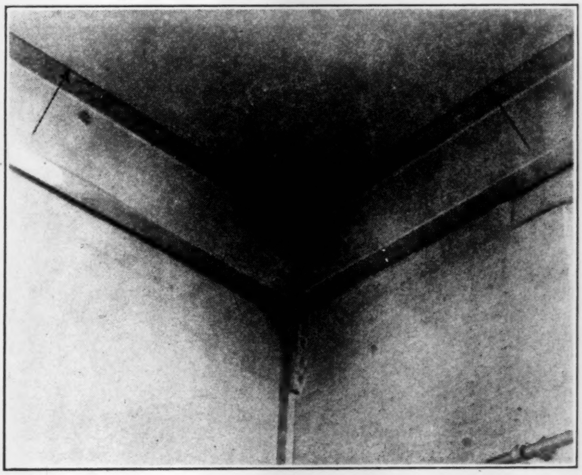

FIG. 2.—Under Side of Slab Curled Up at a Corner of the Building.

All of this evidence seemed to point to a contraction of the upper surface of the floor, which contraction, stressing the surface of the slab, caused the reinforced concrete to curl upward just as a damp board lying on the ground in the sun and drying out and shrinking on its top side will always curl upward at its edges. The wearing course was so strong and hard, and its bond with the main slab so firm, that instead of breaking loose from the slab the contracting top coat had drawn the main slab upward at the edges. But if such is the case, if this is the correct explanation of what has happened, then mortar made of these quarry screenings must contract an unusual amount upon hardening and drying out. It must have contracted very much more than the main slab which shows so few cracks on its under side.

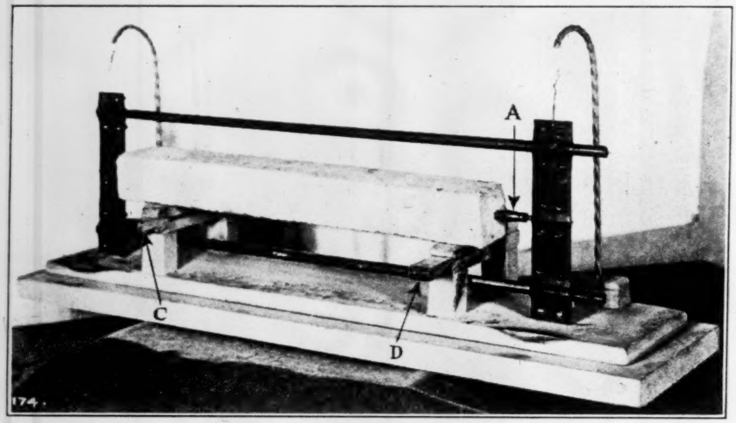

FIG. 3.—Measuring Device, with Specimen in Place.

While such an explanation of this serious cracking sounded almost too freakish to be accepted, yet the evidence seemed to point so plainly to this cause that it was decided to make a series of shrinkage tests of mortar and concrete bars of various aggregates commonly used and including these quarry screenings. Accordingly, a series of test specimens 24 in. long and 2 in. square in section, with small bronze inserts in each end for calipering, were made up in the laboratory of Westinghouse, Church, Kerr and Co., now Dwight P. Robinson and Co. After curing in damp sand, these bars were measured at intervals by means of a micrometer caliper especially arranged for the purpose. The details of the method of making these tests were, briefly, as follows:

A three-compartment wood mold was made up and well waterproofed with a solution of paraffin wax in benzine. Pins were provided in the ends of the mold which were movable and loosely fitted into their holes. The purpose of these pins was to core a small cavity in each end of the specimen for the insertion of a small bronze round beaded pin. These pins were set in place with plaster of Paris when the specimens were removed from the mold 24 hours after making. Materials were proportioned by weight, the mortar specimens being 1:2 and the concrete specimens 1:2:4. Mixing was done by hand, and was quite thorough. The consistency was mushy and was controlled, the amount of mixing water being varied. The mortar or concrete was well tamped into the forms and troweled smooth.

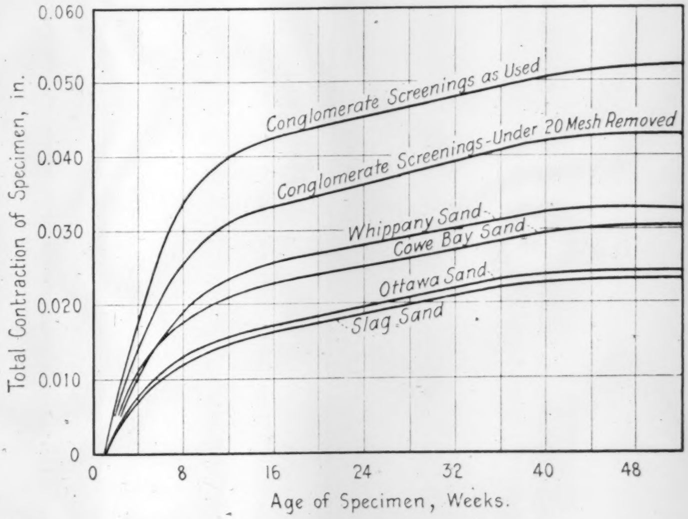

FIG. 4.—Contraction of 1:2 Mortar Specimens. Stored 7 Days in Damp Sand, Thereafter in Air.

Specimens were stored in a damp closet for 24 hours, then removed from the mold and stored as indicated on the curves either in damp sand or in air or in water.

The measurements of length were made with an ordinary inside micrometer rigged up in a frame composed of $\frac{1}{2}$-in. reinforcement rods and strap-iron clamps held together with stove bolts. Fig. 3 shows the device set up for making a measurement and with a specimen in place. The micrometer is shown at *A*, bearing on the head of the bronze pin inserted in the end of the specimen. The wedges *C* and *D* are for the purpose of adjusting the height of the specimen so as to bring the inserts in alignment with the micrometer points. Measurements were made on each specimen every seven days.

The mixtures used were chosen with a view to bringing out several points bearing more or less directly upon the problem presented by the peculiar action of these floors. They included both mortar and concrete containing the conglomerate screenings used in the wearing course of these floors in comparison with screenings of trap rock, granite, slag, and limestone and also with Ottawa sand, Cowe Bay sand and Whippany sand. In the concrete specimens the coarse aggregate was $\frac{3}{4}$-in. screened gravel from Cowe Bay. The cement used was what we call a laboratory sample, a mixture of five brands of cement stored in sealed air-tight metal containers.

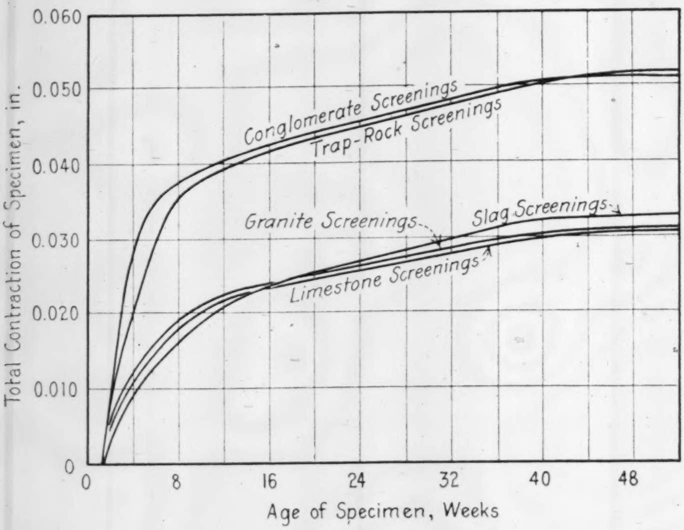

FIG. 5.—Contraction of 1:2 Mortar Specimens. Crushed Rock Screenings, Screened and Recombined to Conform to Mechanical Analysis of "Conglomerate Screenings." Stored 7 Days in Damp Sand, Thereafter in Air.

To ascertain whether the excessive contraction was due to the nature of the screenings used in the wearing course or to the fact that they were unusually fine, two methods were used. First a comparison was made, between (*a*) the conglomerate screenings as used, (*b*) the same screenings with the fines under 20 mesh removed, (*c*) Whippany sand, (*d*) Cowe Bay sand, (*e*) slag sand and (*f*) standard Ottawa sand. The results of this series are shown in Fig. 4. In this and in all succeeding figures the total contraction of the 24-in. specimens in thousandths of an inch is plotted against the age of the specimen in weeks. These curves indicate that while the elimination of the fines considerably lowered the coefficient of contraction, yet these conglomerate screenings with dust eliminated still showed about 80 per cent greater total contraction at the end of a year than standard Ottawa sand.

A second comparison was made between the conglomerate screenings as used and crusher screenings from other rocks commonly used as fine aggregate. These included (*a*) conglomerate screenings as used, (*b*) trap-rock screenings, (*c*) slag screenings, (*d*) granite screenings and (*e*) limestone screenings. In each of these cases, the materials were separated as to size and recombined to conform to the mechanical analysis of the conglomerate screenings used. The results are shown in Fig. 5. It will be noted that trap-rock screenings of similar mechanical analysis behave almost exactly like the conglomerate screenings, while slag, granite and limestone of the same mechanical analysis behave very much alike and all show approximately 60 per cent of the contraction of the conglomerate or the trap-rock screenings.

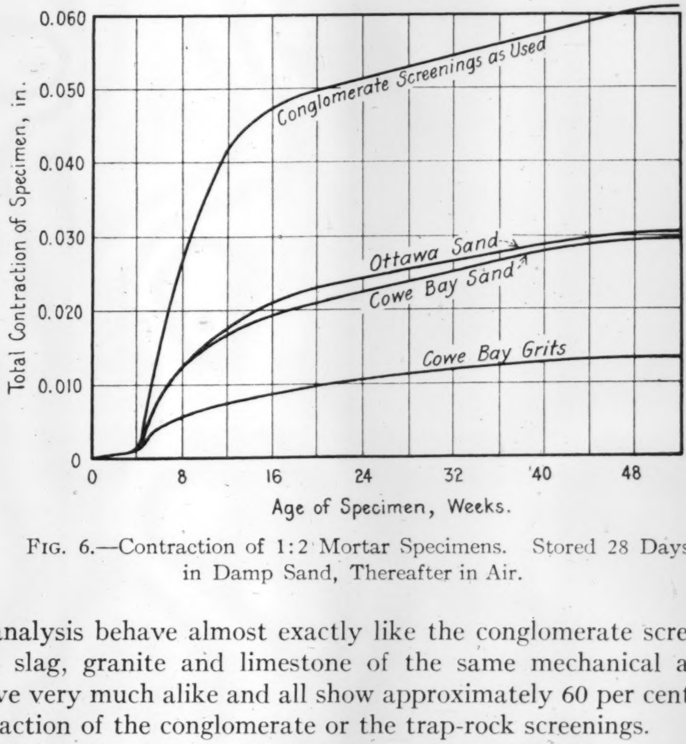

FIG. 6.—Contraction of 1:2 Mortar Specimens. Stored 28 Days in Damp Sand, Thereafter in Air.

From these two series it appears that while the conglomerate screenings even with fines removed contract decidedly more than the sands tested and also much more than some rock screenings of similar mechanical analysis, yet trap-rock screenings are just as active in their influence on contraction in 1:2 mortar.

In the tests just described the specimens were cured by storing in damp sand for 7 days and were thereafter stored in air. In order to determine the effect of a longer curing period, a series of specimens were stored in damp sand for 28 days and thereafter in air. While this series was not made up of the same materials as the first series, yet there are duplications of the conglomerate screenings, Cowe Bay sand and standard Ottawa sand. A comparison of these two sets of curves, Figs. 4 and 6, shows that the longer curing period in damp sand has, in the cases of the conglomerate screenings and Ottawa sand, somewhat increased the total contraction while with Cowe Bay sand the contraction is about the same in both cases. Apparently longer curing does not decrease the amount of contraction, but if anything tends to increase it.

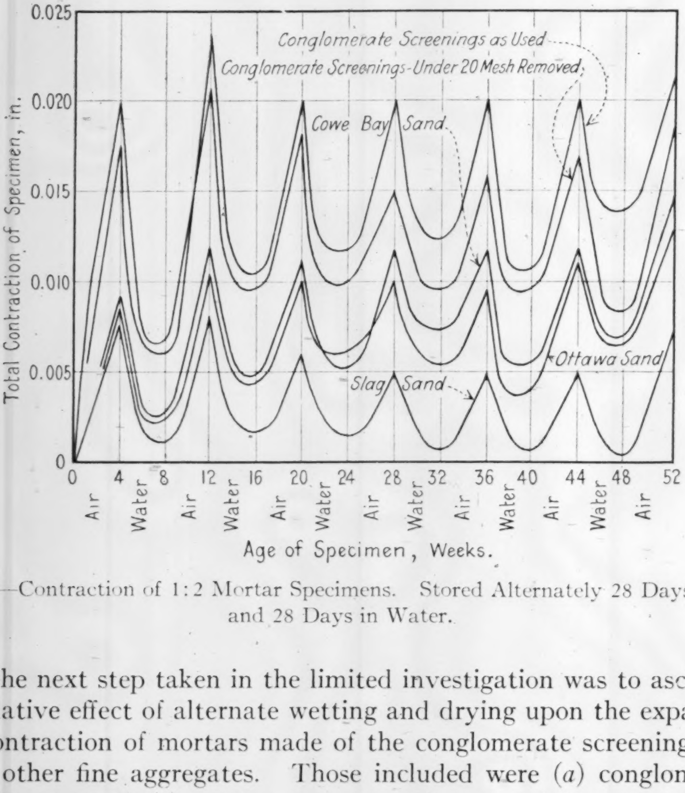

FIG. 7.—Contraction of 1:2 Mortar Specimens. Stored Alternately 28 Days in Air and 28 Days in Water.

The next step taken in the limited investigation was to ascertain the relative effect of alternate wetting and drying upon the expansion and contraction of mortars made of the conglomerate screenings and a few other fine aggregates. Those included were (*a*) conglomerate screenings as used, (*b*) conglomerate screenings remaining on a 20-mesh sieve, (*c*) Cowe Bay sand, (*d*) Ottawa sand and (*e*) slag sand. In this series the specimens were stored for four-week periods alternately in air and in water and measurements made at the time of changing. The results are shown in Fig. 7. It will be noted here, as in Fig. 4, that the elimination of the dust from the conglomerate screenings tends to reduce the volume change. Also it will be noted that these screenings show greater changes due to moisture content than the other materials tested. One very noticeable feature brought out by these curves, however, is the fact that with alternate wetting and drying the progressive change in length so noticeable in the previous curves does not take place. All of these specimens are approximately the same length, when dry, at the end of a year that they were at the end of a month.

Having gone thus far with 1:2 mortars, a few specimens of 1:2:4 concrete were then made up. The first series of concrete specimens was intended to bring out the effect upon contraction of these conglomerate screenings as compared with slag sand, Ottawa sand and Cowe Bay sand. In all cases $\frac{3}{4}$-in. siliceous gravel from Cowe Bay was used as the coarse aggregate. The specimens were stored 7 days in damp sand, thereafter in air. The results are shown plotted in Fig. 8. It will be noted, as might be expected, that total contraction is much less than in the case of 1:2 mortar and that the difference between the various aggregates is greatly diminished. The conglomerate screenings, however, still show the greatest amount of contraction.

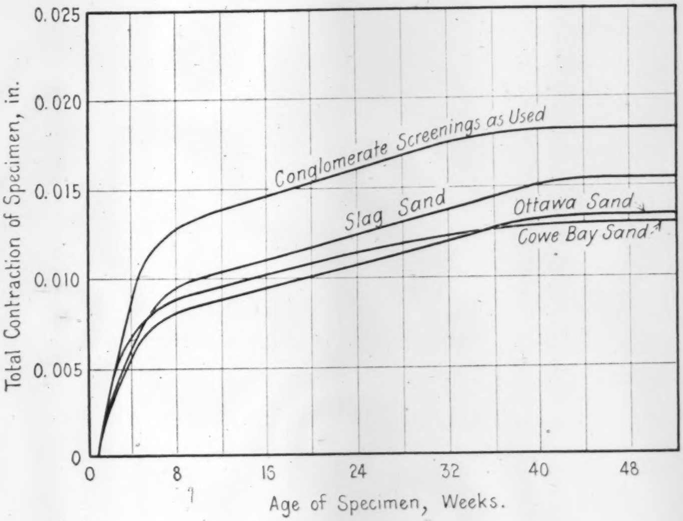

FIG. 8.—Contraction of 1:2:4 Concrete Specimens. Stored 7 days in Damp Sand, Thereafter in Air. Fine Aggregate as Indicated. Coarse Aggregate, $\frac{3}{4}$-in. Screened Gravel from Cowe Bay.

One more series of 1:2:4 concrete specimens was prepared to show the effect of screenings of various rocks, all of the same mechanical analysis as the conglomerate screenings. These included screenings of (*a*) conglomerate, (*b*) trap rock, (*c*) granite, (*d*) slag and (*e*) limestone. The specimens were stored 7 days in damp sand, thereafter in air. The results are plotted in Fig. 9. It will be noted that trap rock has somewhat out-distanced the conglomerate screenings in this series and that the granite, slag and limestone screenings show practically the same contraction as is shown by slag sand, Ottawa sand and Cowe Bay sand of the previous series, Fig. 8. It will also be noted that these specimens appear to have attained their maximum contraction at the age of 32 to 36 weeks and to have remained constant thereafter to the end of the test, which was 52 weeks. In the previous series with concrete specimens (Fig. 8) the shrinkage continued a few weeks longer.

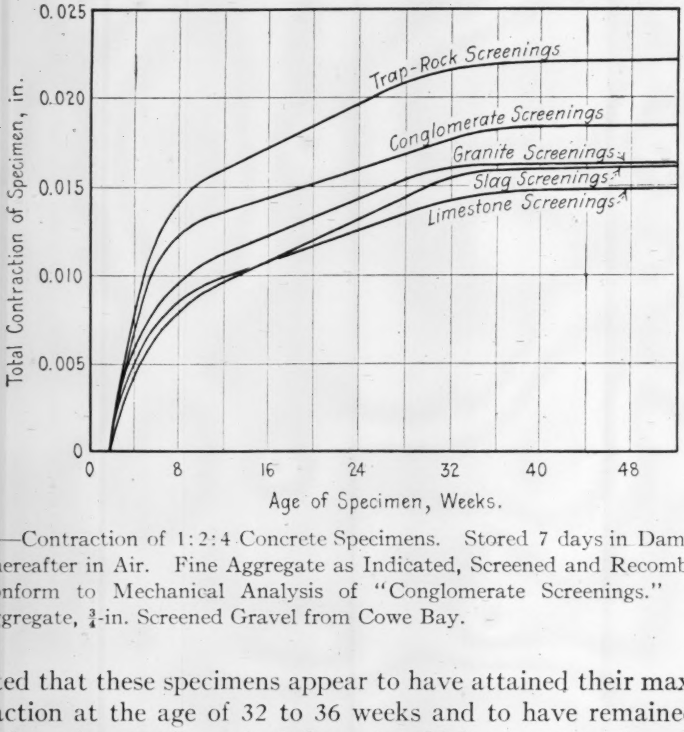

FIG. 9.—Contraction of 1:2:4 Concrete Specimens. Stored 7 days in Damp Sand, Thereafter in Air. Fine Aggregate as Indicated, Screened and Recombined to Conform to Mechanical Analysis of "Conglomerate Screenings." Coarse Aggregate, $\frac{3}{4}$-in. Screened Gravel from Cowe Bay.

It is customary to end papers of this kind with one or more conclusions. In these tests but one specimen of each kind in each series was prepared. Conclusions drawn from single specimens may lead one in the wrong direction. However, it is probably safe to say that this investigation indicates the following:

1. That the aggregates used in rich mortar mixtures for the wearing or finish course of concrete floors may have a marked effect upon the contraction and consequent cracking of the top.

2. That some aggregates may produce such a degree of contraction as to make their use inadvisable.

3. That the contraction of 1:2 mortar is markedly greater than that of 1:2:4 concrete.

In addition, the writer has drawn one more conclusion, namely, that the relation between cracking of concrete and the kind and proportions of the aggregate used is a matter which deserves much more extended and careful study and investigation than is set forth herein.

DISCUSSION

Mr. Chubb. MR. J. H. CHUBB[1].—May I ask about the mixing of the samples? Was the same volume of water used in each case? We know that there is a difference in the expansion and contraction of concrete, between wet and dry mixes. There is quite a variation in the amount of water that these different aggregates will absorb, so if one started with them all wet and used the same amount of water, one would get entirely different results than one would if all of them were dry and the same amount of water was used in the mix. One could expect as much variation as is shown in the figures due to the difference in the water, assuming that the aggregates were all dry and the same amount of water was used in the mix.

Mr. Chapman. MR. CLOYD M. CHAPMAN. What Mr. Chubb says is to some extent true, but I very much doubt whether the greatest practical variation in the water content would account for even a fraction of the differences in contraction found in these tests.

Mr. Chubb. MR. CHUBB. Comparing limestone screenings with a trap rock, for example, even though the consistency is the same to start with, a lot of water is absorbed by the limestone so that the final concrete is very much dryer.

Mr. McMillan. MR. F. R. MCMILLAN.[2]—I had expected to receive in time for this meeting a written discussion of this paper by Mr. M. B. Lagaard, of the University of Minnesota, but it has not arrived. We began experiments in 1911 at the University of Minnesota on the question of the shrinkage of concrete mixtures. Those experiments have been continued by Mr. Lagaard. I will not attempt to give an abstract of the results, because I have not been in touch with the later developments, but I do want to make the point that this subject deserves more attention than has been given it in the past. The discussion here to-day is interesting; the paper is extremely interesting and valuable, but it seems to me that of itself a contraction of 0.05 per cent in one year is deserving of more than passing notice, and this is on the standard aggregates Ottawa and Cowe Bay sands, not the freak aggregate that led Mr. Chapman into this investigation. A shrinkage deformation of 0.05 per cent is about the value that we found in the investigation at the University of Minnesota, this was corroborated

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[1] Manager, Service Bureau, Universal Portland Cement Co., Chicago, Ill.

[2] Associate Engineer, Structural Materials Research Laboratory, Lewis Institute, Chicago, Ill.

Mr. McMillan. by the investigations of Talbot and Richards at the University of Illinois. That represents a shrinkage of about $\frac{5}{8}$ in. in 100 ft., and an initial stress in compression in steel of about 15,000 lb. per sq. in. These two facts alone are sufficient to warrant a very thorough consideration of this phenomenon. In the design of a slab or similar member, there may be some reason for neglecting the initial shrinkage stress, but in the design of reinforced concrete columns where the load and shrinkage act together in producing compression in the steel, it seems that an initial stress in the reinforcement of 15,000 lb. should hardly be neglected.

Mr. Mattimore. MR. H. S. MATTIMORE.[1]—In discussing Mr. Chapman's paper, I wish to say that I am not at all surprised that extensive shrinkage and volumetric changes were noted when stone screenings were used as an aggregate. Stone screenings are highly absorbent and it has been found very difficult to control checking and cracking on structures in which they are used. This feature is recognized by many concrete engineers who eliminate the use of this product.

Mr. Merriman. MR. THADDEUS MERRIMAN.[2]—One of the features disclosed by our investigation is that all cement mixtures do not shrink alike. It is possible that an explanation for this phenomenon may be found in the fact that when water is added to cement, the cement particles are forced apart. Then later, as the water goes off, these cement particles tend to come closer together and so visible shrinkage results. We have lately been experimenting with the new alumina cements, and there is one very marked difference in physical behavior as between these cements and portland cement. The alumina cement seems to repel the water, with the result that when made up the cement particles lie more closely together. The finished product is therefore of greater density. It may be that a solution of some of these shrinkage troubles will be found in a method of treatment which will cause the particles of portland cement to be brought into more intimate relation and lie more closely together when water is added rather than, as in the present product, to become separated from each other. An increase in density is one important feature that is needed in practically all concrete construction. Much of the trouble encountered in the way of disintegration is due to this lack of density. On engineering structures for outdoor exposure no one would think of accepting a brick that had an absorption of from 10 to 15 per cent, yet nearly all concrete shows such an absorption. As a result, water gets into the concrete and freezes, or in passing through dissolves out the solubles

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[1] Engineer of Materials, Pennsylvania State Highway Commission.

[2] Chief Engineer, Board of Water Supply, New York City.

Mr. Merriman. and makes more space for more water and subsequent greater frost action. It will be of interest also to note, in regard to this matter of overcoming the repulsion between the cement particles, that we have had some success in controlling this phenomenon. For instance, we have been able, in an experimental way, to secure from briquettes made with cement mixed with 62 per cent of water a strength at 28 days of well over 500 lb. per sq. in.

Mr. Chapman. MR. CHAPMAN.—In closing the discussion, I have just one point to bring out. It does not seem to me that we can account for this excessive contraction entirely on the basis of the drying out of the water in the specimen. It does not seem to me that a specimen stored in air in the laboratory, which was heated in the winter, would continue to lose moisture for a year. It seems to me a constant moisture content, a balanced condition, would be reached in a shorter period. I would say that two or three months ought to dry out a specimen as much as a year would dry it out; yet this contraction continues in some cases for the full 52 weeks and in others for about 36 or 40 weeks.

CALCIUM CHLORIDE AS AN ADMIXTURE IN CONCRETE

By Duff A. Abrams[1]

Introduction

The use of chemical compounds for hastening the hardening of portland-cement concrete has attracted considerable interest during the past few years. Experience and earlier tests had shown that calcium chloride, or materials having this compound as one of their principal constituents, was probably the most promising for this purpose, and consequently the investigation of the effect of chemical admixtures on the compressive strength of concrete described in this report was confined primarily to such materials.

These tests were begun in cooperation with Committee C-9 on Concrete and Concrete Aggregates of the American Society for Testing Materials.[2] Our investigations covered a much wider range than originally outlined by the committee. They included tests of concrete at different ages for a wide range in mix, consistency and condition of curing, using different percentages of calcium chloride and other admixtures similar in type. A few tests were made using calcium chloride in concrete mixed and cured at low temperatures. This paper gives the results of about 7500 strength tests of concrete and mortar.

These tests were made as a part of the experimental studies of concrete and concrete materials being carried out at the Structural Materials Research Laboratory through the cooperation of Lewis Institute and the Portland Cement Association.

Outline of Tests

Three separate investigations were carried out:

Series 156 comprised compression tests of about 4000 6 by 12-in. concrete cylinders and 1250 2 by 4-in. mortar cylinders; specimens made June to August, 1921.

The following admixtures were used:

Calcium chloride *A* } Samples from different manufacturers
Calcium chloride *B* }
"Cal" furnished by Cal Chemical Co., Hagerstown, Md.
"Vitriflux" furnished by The Granitex Co., New York City.
Magnesium chloride, purchased in Chicago.

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[1] Professor, In Charge of Structural Materials Research Laboratory, Lewis Institute, Chicago, Ill.

[2] See Report of Cooperative Series of Tests on Accelerators, *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part I, p. 223 (1923).

Concrete and mortar tests were made at ages ranging from 2 days to 3 years. The tests on calcium chloride *B* were extended to include wide variations in mixtures and consistencies and four different cements. Tables I to V, also VII, X, and XI, give the principal results of the tests in this series.

Series 158 consisted of compression tests of about 1700 6 by 12-in. concrete cylinders. Tests were made using 0 to 10 per cent of calcium chloride *B* by weight of cement for a wide range of periods of curing in the moist room, followed by air curing. Tests were made at ages of 7 days to 2½ years. In one group five different cements were used. The specimens were made September to December, 1921. The test results of this series are given in Tables VI, VIII and XI.

Series 188 comprised 630 compression tests of 6 by 12-in. concrete cylinders made in a study of the early strength of concrete cured at low temperatures. Tests were made at ages of 1 to 28 days for the following conditions:

(*a*) Specimens made in laboratory, cured in moist room,
(*b*) Specimens made in laboratory, cured outdoors,
(*c*) Specimens made outdoors, cured in moist room,
(*d*) Specimens made outdoors, cured outdoors.

The outdoor temperatures at the time the specimens were made (March 12 to 18, 1924) and for the following few days ranged from about 24 to 37° F. The indoor temperatures were about 68° F. This series of tests was carried out for the most part on concrete without admixtures but in some of the tests calcium chloride *A* was used in the proportion of 3 per cent by weight of the cement. Table IX gives the results of tests in this series.

MATERIALS AND METHODS

Cement.—All tests were made with portland cement purchased in Chicago. The physical tests of the cements are given in Table XIII; chemical analyses in Table XV. Cement A was used in Series 156, except in the tests of different cements, where brands B, C and D were also used. Most of the specimens in Series 158 and all of those in Series 188 were made with "Laboratory Cement," consisting of a mixture of four brands purchased in Chicago. In a part of Series 158, cements A, B, C, and D were used separately; these were the same brands used in Series 156 but from later lots.

Aggregate.—The aggregate for concrete consisted of sand and pebbles from Elgin, Ill., graded 0 to 1½ in. It was screened into four sizes (0 to No. 4, No. 4 to ⅜ in., ⅜ to ¾ in. and ¾ to 1½ in.) and recombined to a predetermined sieve analysis (fineness modulus 5.68). Aggregates graded in this way are generally used in our laboratory to reduce the variations in grading to a minimum. The mortar tests in Series 156 were made using the same sand (graded 0 to No. 4, fineness modulus 3.04).

Admixtures.—Six different admixtures were used; two lots of commercial calcium chloride, Cal (standard and low chlorine), Vitriflux and magnesium chloride.

Two brands of commercial calcium chloride were obtained from different manufacturers and are designated as *A* and *B*. Brand *B* was used in most of the tests of both Series 156 and 158, although the lots used in the two series were purchased at different times. The commercial calcium chlorides contained about 75 per cent of $CaCl_2$ with small amounts of impurities, principally magnesium and sodium chloride; the magnesium chloride content was less than 0.5 per cent.

Two lots of Cal were used, standard and low chlorine. The material comes as a white powder. The standard contained about 25 per cent of calcium chloride, or about 16 per cent of chlorine; the low-chlorine Cal contained 17 per cent of calcium chloride, or 11 per cent of chlorine. For these tests the quantities are expressed as percentages of weight of cement. *Technologic Paper No. 174,* U. S. Bureau of Standards, 1920, "Effect of Cal as an Accelerator of the Hardening of Portland Cement Mixtures," by R. N. Young, states that "Cal is a material obtained by pulverizing the dried and undried product resulting from a mixture of either quicklime, or hydrated lime, calcium chloride, and water."

Vitriflux is a solution of calcium chloride in water (about 34 per cent of $CaCl_2$). The quantities of the liquid used are reported in the tables as percentages by weight of cement.

The magnesium chloride was of the grade commercially known as "flake" and contained about 46 per cent of $MgCl_2$.

Table XIV gives partial chemical analyses of the admixtures showing the amount of $CaCl_2$ and the combined chlorine.

Test Pieces.—The concrete specimens were 6 by 12-in. cylinders, and the mortar specimens were 2 by 4-in. cylinders. Concrete specimens were made in accordance with methods recommended in the Tentative Methods of Making Compression Tests of Concrete (Serial Designation: C 39 – 21 T) of the American Society for Testing Materials. The methods used in making the mortar specimens differed only in minor details from those outlined in the Tentative Specifications and Tests for Compressive Strength of Portland Cement Mortars (Serial Designation: C 9 – 16 T) of the American Society for Testing Materials.

The concrete cylinder forms were of cold-drawn steel tubing, slotted along one element. In making the specimens, the forms were placed on machined cast-iron plates. The concrete was placed in 3 layers, each layer being rodded 30 times with a ⅝-in. bullet-pointed steel rod. The specimens were capped 3 to 4 hours after molding with neat cement (which had been allowed to stand 3 to 6 hours after mixing) and the caps brought to a true plane by means of machined plates which were worked down to the tops of the forms and left in place until the forms were removed after 16 to 20 hours.

Proportioning and Mixing.—In Series 156 and 158, each concrete specimen was made from a batch of about ⅕ cu. ft., proportioned separately and mixed with a bricklayer's trowel in a shallow metal pan. The proportions of cement and aggregate are expressed as one volume of cement to a given number of volumes of dry, rodded aggregate[1] mixed as used. The quantities of each batch were determined by weight. For example, a batch of 1:5.2 concrete consisted of 3.82 lb. of cement, and 27.0 lb. of aggregate; the quantity of water varied from 2.00 to 2.50 lb. for concrete of normal consistency, depending on the kind and amount of admixture used.

In Series 188 the concrete was mixed with shovels on a metal plate in batches of sufficient size to make seven 6 by 12-in. cylinders.

The mortar specimens in Series 156 were of 1 : 2½ mix by volume.

Consistency.—The plasticity of the concrete was measured by means of the "flow table"[2] using fifteen ½-in. drops in 10 seconds. The test consists of jigging a truncated-cone-shaped mass of concrete on a special table, and measuring the bottom diameter after the test. The concrete was molded in a truncated cone having a top diameter of 6¾ in., a bottom diameter of 10 in., and a height of 5 in. The bottom diameter after the test, expressed as a percentage of the original diameter, is the "flow."

For relative consistency 1.00, sufficient water was used to give a flow of about 180. This represents a consistency such as would be used in machine-finished concrete road construction and corresponds to a slump of about ½ to 1 in. For a relative consistency of 1.10, 10 per cent more water was used than for relative consistency 1.00; similarly for other consistencies.

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[1] If these proportions are to be reduced to the common terms of separated volumes of damp aggregates measured loose, account must be taken of the differences in the volumes occupied by separated fine and coarse aggregate and the same materials when mixed. Account must also be taken of the bulking of the fine and coarse aggregate due to loose measurement and the presence of moisture. For example, a 1:5.2 mix based on dry and rodded mixed materials is approximately equivalent to a 1:2:4 mix of dry and rodded separated aggregates, which in turn is nearly the same as a 1: 2½: 4½ mixture in terms of the damp and loose materials commonly encountered in the field.

[2] For a description of the flow table see, "Time of Set of Concrete," by Watson Davis, *Proceedings*, Am. Soc. Testing Mats., Vol. 21, p. 995 (1921).

Curing and Testing.—In general, the specimens for Series 156 were cured in a room in which the air was saturated with moisture and in which a uniform temperature of about 70° F. was maintained. For Series 158 and 188, specimens were cured in a moist room and in air as indicated in the tables.

Compression tests of concrete were made in a 200,000-lb. universal testing machine; mortar tests were made in a 40,000-lb. testing machine. The load was applied through a spherical bearing block placed on top of the specimen. The specimens having been carefully capped as previously described, no additional bedding was required.

DATA AND DISCUSSION

Outline of Results.—This report covers primarily an investigation of the effect of admixtures of commercial calcium chloride and of similar materials on the compressive strength of concrete made and cured under *normal temperature conditions.* In addition a few preliminary tests were made at temperatures near freezing. In view of the limited number of tests at low temperatures, the results cannot be considered as a comprehensive study of the value of calcium chloride for use in concrete work carried out in cold weather.

Some of the tests were made with proprietary compounds consisting essentially of a calcium chloride base. In one series, parallel tests were made with magnesium chloride.

This investigation does not cover the curing of concrete by spreading calcium chloride over the surface;[1] nor were any tests made to determine the merits of so-called "floor hardeners."

The effect of the various admixtures on the strength of concrete is discussed in relation to the usual considerations which arise in practice, such as differences in mix, consistency, curing, etc.

The following outline will facilitate the study of the test data; reference is made to the tables and diagrams which give the related data from the tests:

Type of Admixture:

Five different admixtures in varying amounts are compared using the same cement, mix, consistency and curing condition. Tests of concrete and mortar were made at ages of 2, 7 and 28 days, 3 months, 1 and 3 years; concrete cured in moist room and mortar in water. until tested. Tables I and II and Figs. 1 and 2 give the test results.

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[1] For a discussion of this subject see, "An Investigation in the Use of Calcium Chloride as a Curing Agent and Accelerator of Concrete," by H. F. Clemmer and Fred Burggraf, *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 296 (1923). Further field and laboratory tests of this kind are now under way by the Structural Materials Research Laboratory.

Quantity of Cement (Mix):

Five different mixes (1:7, 1:5.2, 1:4, 1:3 and 1:2) were used with the following percentages of calcium chloride *B*: 0, 1, 2, 4, 7 and 10. All specimens were mixed to a relative consistency of 1.00 and cured in the moist room until tested at ages of 2, 7, and 28 days, 3 months, 1 and 3 years. Table III and Figs. 3, 4, 6, 12 and 14 give the test results.

Quantity of Mixing Water (Consistency):

Five different consistencies (0.90, 1.00. 1.10, 1.25, and 1.50) were used with the following percentages of calcium chloride *B*: 0, 1, 2, 4, 7 and 10. Mix 1:5.2. All specimens were cured in the moist room until tested at ages of 2, 7, and 28 days, 3 months, 1 and 3 years. Table IV and Figs. 5, 6, 13 and 14 give the test results.

Water-Ratio-Strength Relation:

The different mixes and different consistencies indicated above provided concrete of a wide range in water-cement ratio. Data are given in Tables III and IV and in Fig. 6.

Curing Condition:

Specimens cured in moist room, water, and in air were compared in Series 156; Series 158 included specimens cured in moist room for a part of the curing period, remainder in air. Calcium chloride *B* was used in the following percentages: 0, 1, 2, 4, 7 and 10. In Series 156 all specimens were of 1:5.2 mix, relative consistency 1.00 and tested at 28 days, 3 months, 1 and 3 years. In Series 158 specimens were tested at 7 and 28 days, 3 and 6 months, 1 and 2½ years. Table V and Figs. 7 and 8 give results from Series 156. Table VI and Figs. 9 and 10 give results from Series 158.

Brand of Cement:

Tests of different cements were made in Series 156 using calcium chloride *B* in both concrete and mortar, and in Series 158 in concrete only. The same four brands of cement were used in both series but from different lots. Table VII and Fig. 11 give the results from Series 156 for 1:5.2 concrete and 1:2.5 mortar of relative consistency 1.00, tested at 2, 7 and 28 days, 3 months, 1 and 3 years with 0 and 4 per cent of calcium chloride. Table VIII gives the results from Series 158 for 1:5.2 concrete, relative consistency 1.00, tested at 28 days, 3 and 6 months, 1 and 2½ years, for percentages of calcium chloride of 0, 1, 2, 4, 7 and 10.

Age at Test:

In all of the studies of the effect of calcium chloride on the strength of concrete, the age at test is involved. The test data are considered with respect to the influence of the age at test on the action of the admixtures. Figs. 12, 13 and 14 show the results for tests of different mixes and consistencies. Fig. 15 shows the results for different admixtures.

Miscellaneous Tests:

These tests give data on the influence of calcium chloride on the time of setting of cement (Table XIV) on the "flow" (Table XII) and some data from tests of concrete made at low temperatures (Table IX and Fig. 16).

Summary Tables:

Tables X and XI summarize the results from Series 156 and 158.

Strength-Ratio.—In studying the effect of the various admixtures under the different conditions of test it is convenient to compare the strengths obtained with the strength of the corresponding concrete without admixture (here referred to as plain concrete). Thus, for each value of strength given in the tables there is a corresponding "strength-ratio," which expresses the strength as a percentage of the strength of the plain concrete, identical as to age, mix, consistency, brand of cement, and curing conditions. Obviously the strength-ratio for the plain concrete is 100 per cent.

The "maximum strength-ratios" given in Tables X and XI are the highest values shown by the curves representing the variation in strength due to the amount of admixture for the given set of conditions. In these two tables the per cent of admixture for which the highest values were found is also given.

Strength of Concrete Without Admixture.—The values for concrete strength are in general the average of 8 to 10 tests. In order to secure more reliable values for a basis of comparison the tests of plain concrete were duplicated at different points in Series 156; in some instances as many as 25 tests were averaged.

The average compressive strengths of 1:5.2 concrete of relative consistency 1.00 without admixtures were:

Series	Specimens Made	Compressive Strength, lb. per sq. in.						
		2 days	7 days	28 days	3 months	6 months	1 year	3 years
156	June–August, 1921.	950	1940	3310	4170	....	4320	5020
158	September–December, 1921.	...	1310	2640	3380	4110	4790	....

Tables III, IV, VII and VIII show the strengths for other mixes, consistencies, cements, etc.

Effect of Type of Admixture on the Strength of Concrete.—Figs. 1 and 2 show the effect of the different admixtures on the strength of concrete compared on the basis of the percentage of admixture and chlorine content. Fig. 1 shows that with the exception of magnesium chloride the different admixtures behave similarly, showing increases in strength up to a certain percentage of admixture beyond which the strength gradually decreased. The "optimum" percentages were not the same for the different admixtures. However, when comparisons are made on the basis of chlorine content as in Fig. 2, the high points of the curves fall approximately over each other, within the range of from 1 to 2 per cent of chlorine by weight of cement.

The increase in strength due to the different admixtures was not the same for the same percentages of chlorine, although for the commercial brands of calcium chloride and standard Cal the results did not differ greatly.

The commercial samples of calcium chloride gave approximately the same results except for the 2-day tests, in which brand *A* gave somewhat higher strengths. The maximum strength-ratios were obtained with from 2 to 4 per cent of calcium chloride by weight of the cement. For quantities greater than about 4 per cent the strength gradually declined and fell below "par" at about 6 to 8 per cent by

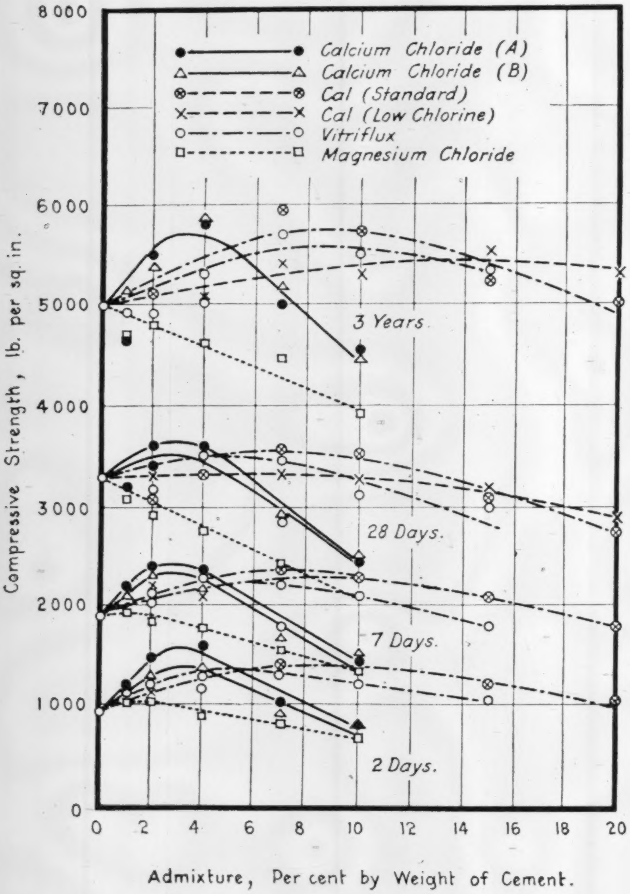

FIG. 1.—Effect of Type of Admixture on the Strength of Concrete.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Mix 1 : 5.2 by volume; relative consistency 1.00.
Each value is the average of from 4 to 10 tests made on different days.
Data from Table I; curves for 3 months and 1 year omitted.

weight of cement; with 10 per cent of calcium chloride the strength-ratios ranged between 70 and 90 per cent.

The following maximum strength-ratios for calcium chlorides *A* and *B* in Series 156 and for *B* in Series 158, show the close agreement between the two brands and the separate lots of brand *B* tested at different times with different concrete materials.

Age at Test	Maximum Strength-Ratio, per cent			
	Series 156		Series 158	Average
	Calcium Chloride *A*	Calcium Chloride *B*	Calcium Chloride *B*	
2 days	170	147	...	158
7 days	125	124	123	124
28 days	110	109	106	108
3 months	112	109	108	110
1 year	117	119	96	111
3 years	118	116	...	117

More detailed discussions of the effect of calcium chloride are given below.

The effect of Cal on the strength of concrete was similar to that of commercial calcium chloride. The maximum acceleration in strength due to Cal was generally found at 7 and 10 per cent as compared with 2 to 4 per cent for commercial calcium chloride. The chlorine content of the optimum percentages of Cal and calcium chloride was about the same (1 to 2 per cent). See Tables I, II and X and Figs. 1 and 2. The maximum strength-ratios for standard Cal at different ages (Table X) were: 2 days, 151 per cent; 7 days, 123 per cent; 28 days, 107 per cent; 3 months, 107 per cent; 1 year, 121 per cent; 3 years, 119 per cent.

Vitriflux consisted of a 34 per cent solution of calcium chloride in liquid form which was placed in the mixing water in amounts corresponding to 1, 2, 4, 7, 10 and 15 per cent by weight of cement. The effectiveness of this material was approximately proportional to the amount added, up to about 7 per cent by weight of the cement, where the maximum strength was obtained. The following maximum strength-ratios were found for about 7 per cent: 2 days, 138 per cent; 7 days, 115 per cent; 28 days, 106 per cent; 3 months 108 per cent; 1 year, 109 per cent; 3 years, 114 per cent. The chlorine content for 7 per cent of Vitriflux was approximately the same as for 2 to 4 per cent of commercial calcium chloride. At ages earlier than 28 days, the maximum effect of Vitriflux was considerably less than that shown by the average for calcium chloride. The strength-ratios for Vitriflux (7 per cent) were 138 per cent for 2 days and 115 per cent for 7 days as compared with 158 per cent and 124 per cent for the average of calcium chloride.

The magnesium chloride was received in flake form and was composed of about 46 per cent magnesium chloride and 54 per cent water.

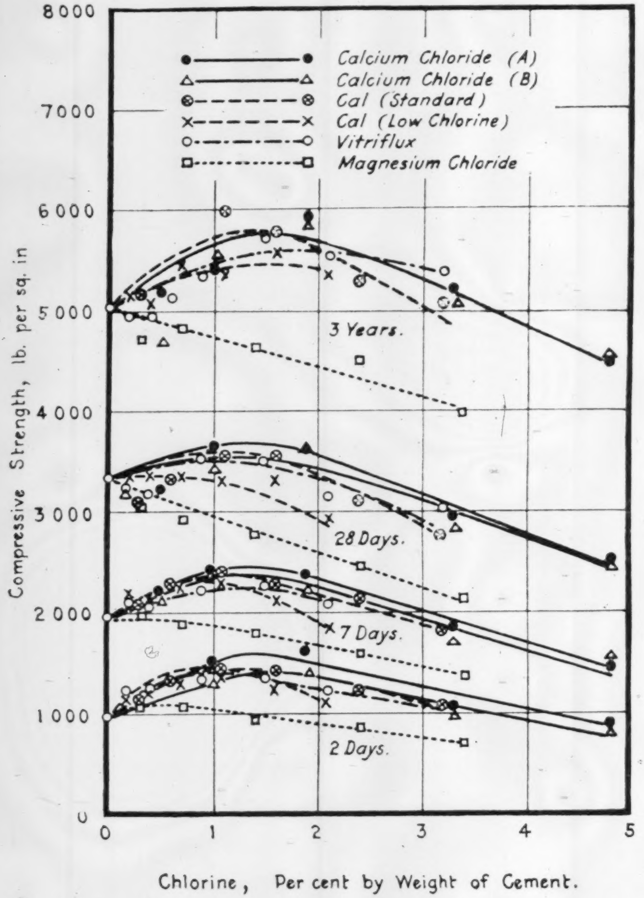

FIG. 2.—Effect of Type of Admixture on the Strength of Concrete.

Same data as in Fig. 1, except admixture expressed in terms of chlorine content. Data from Table I; curves for 3 months and 1 year omitted.

It was put into solution in the mixing water in amounts corresponding to 1, 2, 4, 7 and 10 per cent by weight of cement. In 1 : 5.2 concrete, magnesium chloride gave a slight increase in strength for the 1 and 2-per-cent admixture at 2 days and normal strength at 7 days but *reduced* the strength of concrete for all other conditions. At 28

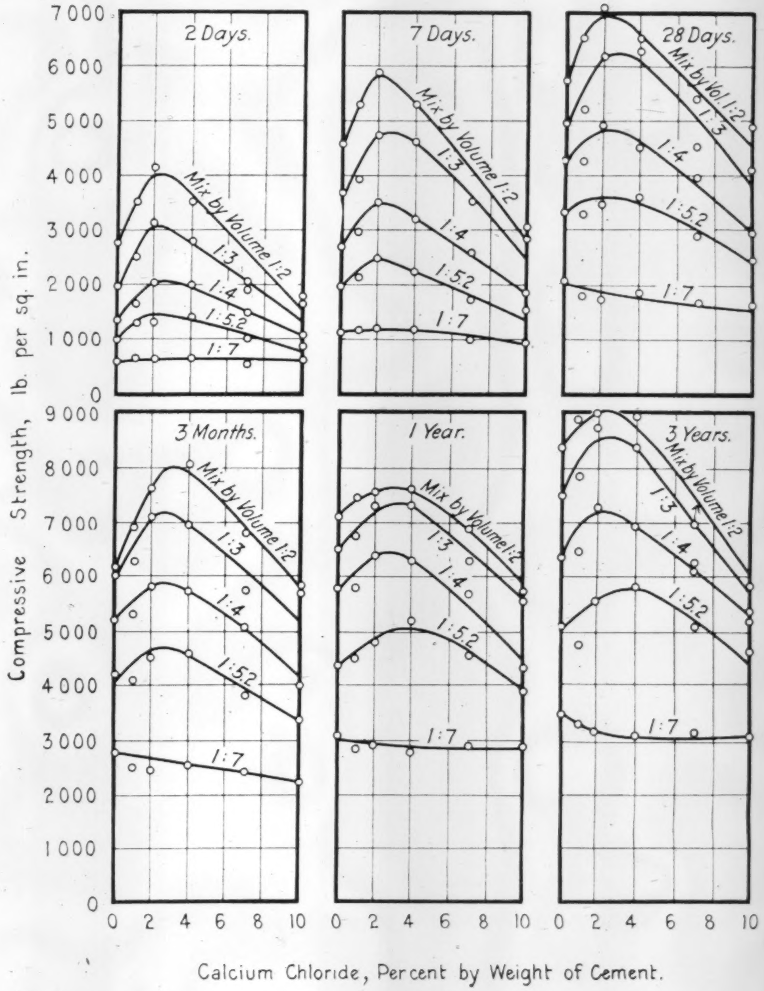

FIG. 3.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Mix.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Each value is the average of 5 tests made on different days.
Calcium chloride *B* was used.
Data from Table III.

days the strength-ratios were: 1 per cent magnesium chloride, 94 per cent; 2 per cent, 88 per cent; 4 per cent, 84 per cent; 7 per cent, 74 per cent; 10 per cent, 64 per cent. It will be seen by reference to Fig. 1 that the reduction in strength was approximately proportional to the quantity of magnesium chloride present.

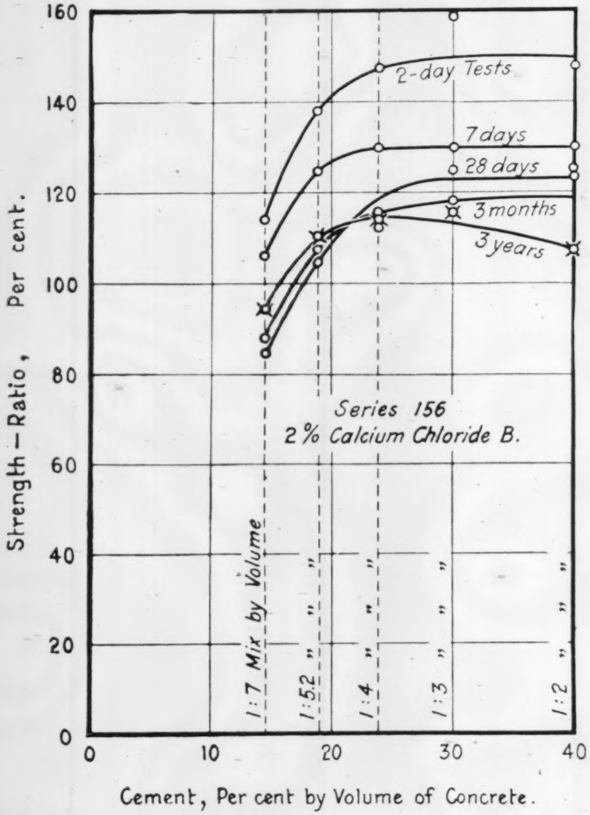

FIG. 4.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Mix.

Strength-ratios from Table III for 2 per cent calcium chloride *B*.
Same data used in Fig. 3.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.
Curve for 1 year omitted.

Effect of Calcium Chloride as Influenced by the Quantity of Cement.—Table III and Figs. 3 and 12 give the results of compression tests of 5 different concrete mixtures using calcium chloride up to 10 per cent by weight of the cement. Fig. 3 shows that the strength of the concrete was increased at all ages by the addition of calcium chloride, except for the 1:7 mix at ages greater than 7 days. The maximum strength-ratios occurred at from 2 to 4 per cent for all mixes. For the 2-day tests, they were: 1:7 mix, 120 per cent; 1:5.2, 147 per cent; 1:4, 149 per cent; 1:3, 159 per cent; 1:2, 149 per cent.

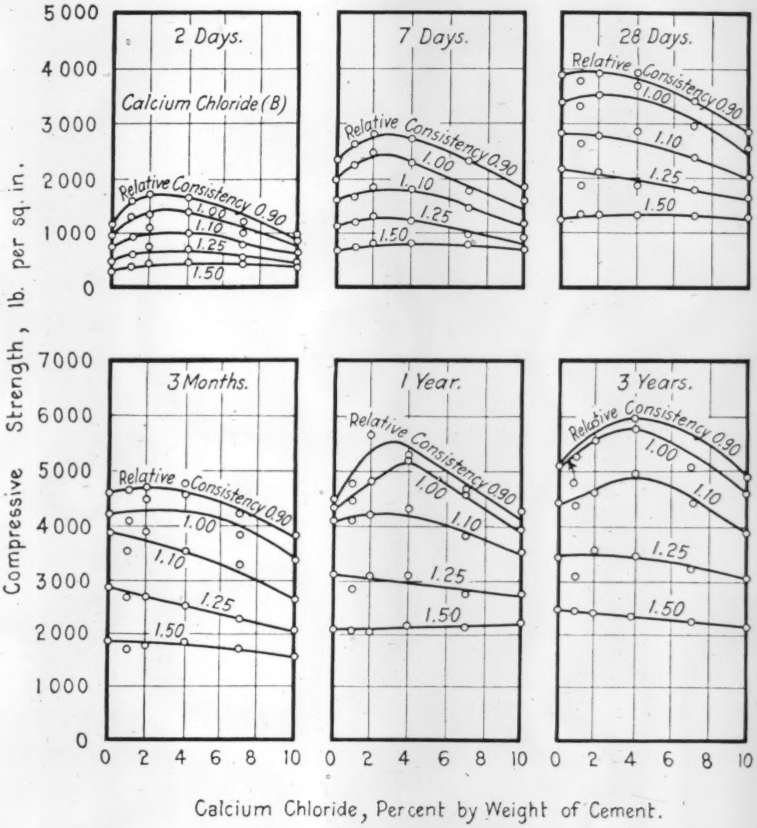

FIG. 5.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Consistency.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Mix 1: 5.2 by volume.
Each value is the average of 5 tests made on different days.
Data from Table IV.

Percentages of calcium chloride greater than 6 to 8 per cent *reduced* the strength at all ages.

Fig. 4 shows the relation of strength-ratio to cement content for 2 per cent of calcium chloride, the percentage for which the maximum values were generally obtained. With increase in the amount of cement up to 23.7 per cent of the volume of the concrete (1:4 mix) the strength-ratios increased at all ages; for the richer mixes the strength-ratios were practically constant for a given age.

In studying the effect of calcium chloride the gain in strength in *pounds per square inch*, as well as the *percentage* gain as measured by strength-ratio must be kept in mind. Reference to Table III and Fig. 14 shows that the increases in strength in pounds per square inch at all ages for 2 per cent of calcium chloride were about as follows:

Mix	Relative Consistency	Increase in Strength, lb. per sq. in
1:7	1.00	Shows a loss after 7 days
1:5.2	"	400
1:4	"	700
1:3	"	1200
1:2	"	1300

It is important to note that the increases in strength in pounds per square inch for a given mix are approximately constant for all ages.

Effect of Calcium Chloride as Influenced by Quantity of Mixing Water.—Table IV and Figs. 5 and 13 give the results of tests on concrete of 1:5.2 mix at ages of 2 days to 3 years for relative consistencies 0.90, 1.00, 1.10, 1.25, and 1.50. The "flows" for the first three consistencies were about 155, 170, and 205; the flow table was not large enough to permit of the determination of the flow for relative consistencies 1.25 and 1.50. The results of flow tests are given in Table XII.

For the 2 and 7-day tests the effect of calcium chloride as measured by the maximum strength-ratios, which in nearly every case corresponded to 2 per cent of admixture, was practically independent of the consistency of the concrete. At later ages the behavior was somewhat erratic and in general strength-ratios below 100 per cent were obtained with the wetter concretes for all percentages of calcium chloride. At 2 days the maximum strength-ratios were: relative consistency 0.90, 153 per cent; 1.00, 147 per cent; 1.10, 144 per cent; 1.25, 159 per cent; 1.50, 146 per cent (See Table XI). At 7 days the average of the maximum strength-ratios for all consistencies was about 120 per cent.

Water-Ratio-Strength Relation for Concrete.—The data obtained from the tests made on the concrete of different mixes and consistencies permits a study to be made of the general effect of quantity of mixing water on strength.

The results of tests on plain concrete and on concrete with 2 per cent of calcium chloride are plotted in Fig. 6 for ages of 2, 7 and 28 days, and 3 years. The curves for 3 months and 1 year were of similar form, but were omitted in order to avoid confusion. Similar curves may be drawn for other percentages of calcium chloride. In these tests the quantity of mixing water was varied by:

(*a*) Change in mix (relative consistency 1.00; Table III).
(*b*) Change in consistency (1: 5.2 mix; Table IV).

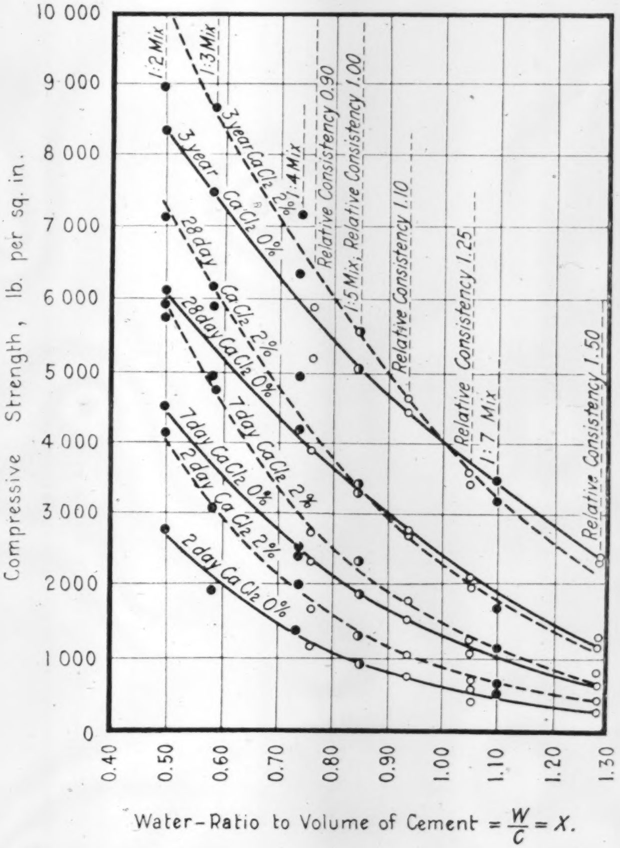

FIG. 6.—Water-Ratio-Strength Relation for Concrete.

Compression tests of 6 by 12-in. concrete cylinders cured in moist rōom.
Data plotted for "plain" concrete and concrete containing 2 per cent of calcium chloride *B*
Data from Tables III, IV and XII.

The results of the tests are consistent and show the importance of the water-ratio-strength relation which has been pointed out in other publications of this laboratory. Increasing the quantity of mixing water produced exactly the same effect as reducing the quantity of cement in the batch. A 1:5.2 mix of relative consistency 1.25 (25 per cent more water than required for "normal" consistency) gave a strength at 28 days of 2100 lb. per sq. in. (See Fig. 6). This strength is about the same as that of a 1:6½ mix of relative consistency 1.00. A 1:5.2 mix of relative consistency 1.50, which is not

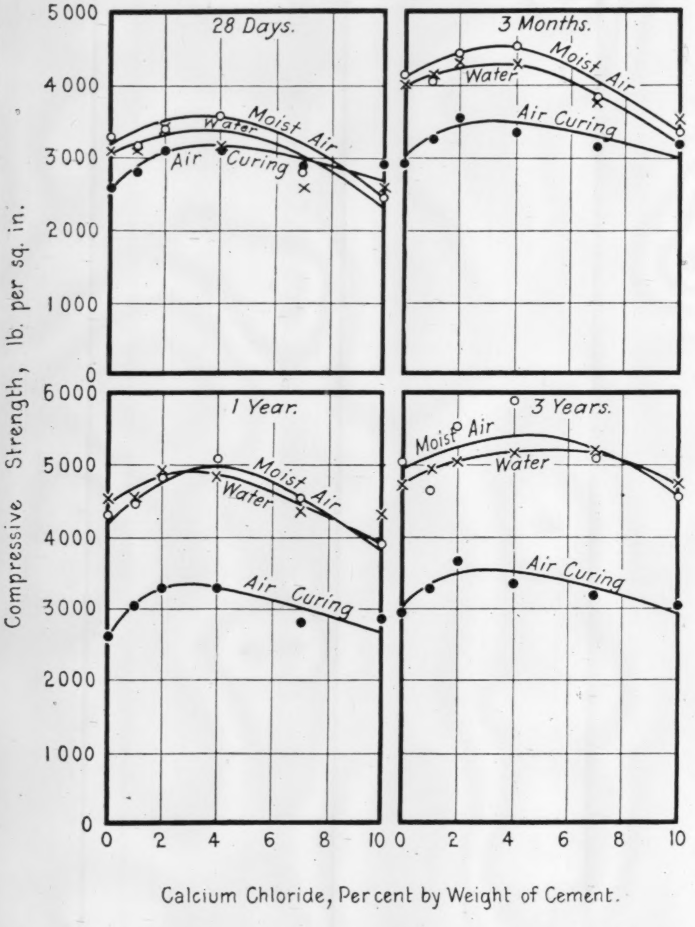

FIG. 7.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Condition of Curing.

Compression tests of 6 by 12-in. concrete cylinders.
Mix 1: 5.2 by volume; relative consistency 1.00.
In general, each value is the average of 9 tests made on different days.
Calcium chloride *B* was used.
Data from Table V.

as wet as concrete frequently used, gave a much lower strength than a 1:7 mix of relative consistency 1.00 ("normal" consistency).

The water-ratio-strength curves in Fig. 6 for concrete with 2 per cent of calcium chloride are similar in form to those for plain concrete. For the lower water-ratios (richer mixes and drier consistencies) the curves for 2 per cent calcium chloride show considerably higher strengths than the curves for plain concrete at all ages. However, the difference in strength becomes smaller as the water-ratio increases and at the later ages the strength for 2 per cent of calcium chloride is lower than that of the plain concrete.

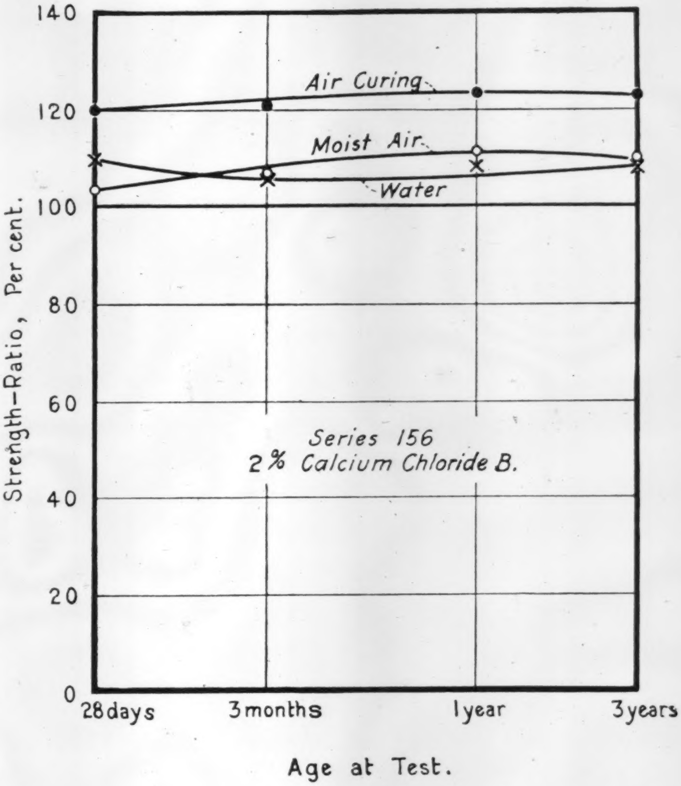

FIG. 8.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Condition of Curing.

Age plotted to logarithmic scale.
Strength-ratios from Table V for 2 per cent calcium chloride *B*.
Same data used in Fig. 7.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.

Effect of Calcium Chloride as Influenced by Curing Condition.—Tests were carried out on concrete cured under different conditions. In Series 156 the following curing conditions were used for 1:5.2 concrete containing calcium chloride in amounts of from 1 to 10 per cent and tested at ages of 28 days to 3 years:

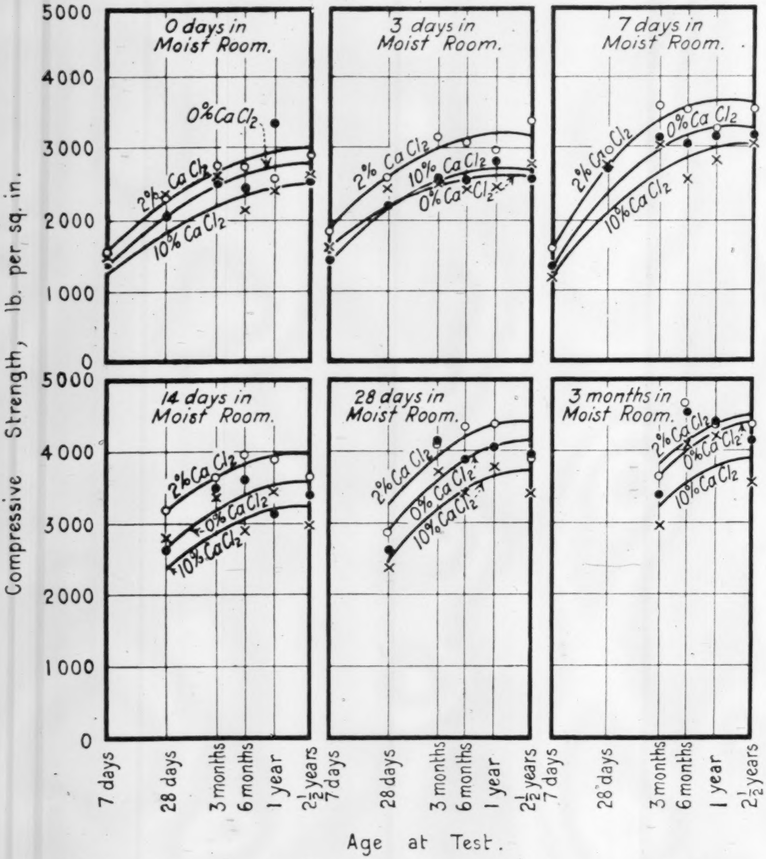

FIG. 9.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Condition of Curing.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room for period indicated and remainder in air.
Age plotted to logarithmic scale.
Mix 1:5.2 by volume; relative consistency 1.00.
Each value is the average of 5 tests made on different days.
Calcium chloride *B* was used.
Data from Table VI.

(*a*) Moist room,
(*b*) Water,
(*c*) Air of laboratory.

The results of these tests are given in Figs. 7 and 8. Fig. 7 shows that in general concrete cured in the moist room and in water had essentially the same strength at each age. In general the air-cured specimens gave considerably lower strengths than those cured in the moist room. At 28 days and 3 months, the differences in strength between the air-cured and moist-room-cured specimens decreased as calcium chloride was added. At 28 days, the air-cured specimens with 10 per cent calcium chloride were somewhat stronger than the specimens cured in water or moist room.

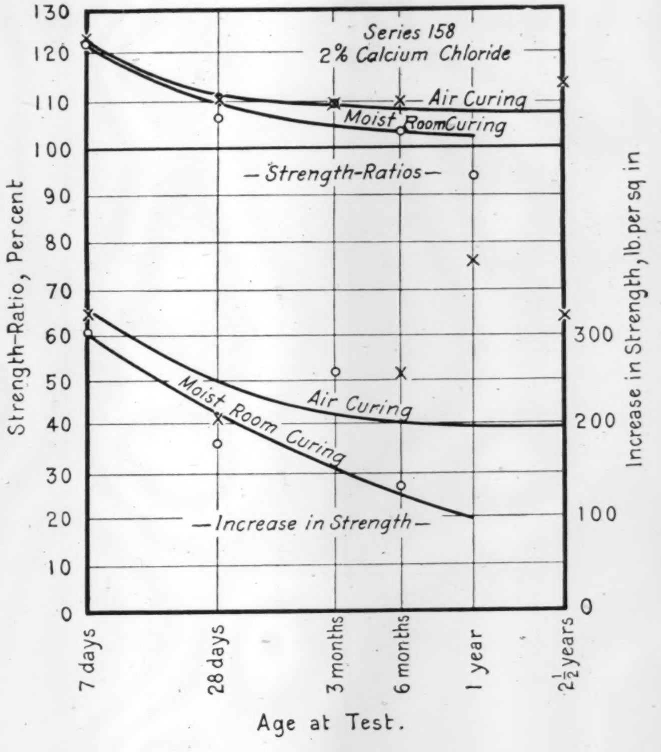

FIG. 10.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Condition of Curing.

Age plotted to logarithmic scale.
Same data used in Fig. 9.
Increase in strength shown for 2 per cent calcium chloride *B*.
Data from Table VI.

Fig. 8 shows that the strength-ratios for air-cured concrete containing 2 per cent of calcium chloride were about 125 per cent for all ages. The strength-ratios for moist-air and water curing were essentially the same at all ages and averaged about 108 per cent.

Fig. 9 gives the results from Series 158 for 1:5.2 concrete tested at ages ranging from 7 days to 2½ years. Calcium Chloride in percentages of from 0 to 10 per cent was used. These specimens were cured for periods in the moist room ranging from 0 days to 3 months followed by curing in the dry air of the laboratory. Curves for plain concrete and for concrete with 2 and 10 per cent of calcium chloride are shown. A striking parallelism between the curves for the plain concrete and those for concrete containing calcium chloride is evident for the different conditions of curing. It can also be shown by these curves that for certain combinations of moist-air curing followed by dry-air curing the strength is greater than when cured the entire period in moist air. This is in accordance with the results of other investigations which show that when the specimens are allowed to dry out before testing greater strengths are obtained. When the curing period in the moist room was relatively short compared to the age at test the curves show that moist-room curing gave the higher strengths.

The comparison between the relative effect of moist and dry curing on the action of calcium chloride can best be seen from Fig. 10, where it will be observed that at the later ages the effect of calcium chloride is somewhat more pronounced for air curing than for moist curing; at the early ages the effect of calcium chloride is about the same for both curing conditions.

Tests were made in Series 188 on the early strength of concrete made at low temperatures. Four separate conditions were used as follows:

Specimens made in the laboratory, cured in the moist room;
Specimens made in the laboratory, cured outdoors;
Specimens made outdoors, cured in the moist room;
Specimens made outdoors, cured outdoors.

A 1:5 concrete of relative consistency 1.25 (slump 8 in.) was used. The concrete was mixed in batches sufficient to make seven 6 by 12-in. concrete cylinders for test at ages of 1 day to 3 months. The outdoor temperatures during the time the specimens were made and for a few days following ranged from 24 to 37° F.; the indoor temperature was about 68° F. Parallel tests were made for plain concrete and for 3 per cent calcium chloride. Tests on effect of temperature of mixing water for concrete made outdoors and cured outdoors at low temperatures were also carried out. The results of these tests are given in Table IX; the results of the parallel tests using 0 and 3 per cent calcium chloride are shown in Fig. 16.

In Fig. 16, the Curve *S* for strength of concrete made in the laboratory and cured in the moist room at normal temperatures is taken as a standard for comparison, and to facilitate the study of the data is repeated in each of the small diagrams.

In general the calcium chloride specimens in this Series gave effects similar to those mentioned above. For the specimens made and cured outdoors at low temperatures, the calcium chloride seemed to be somewhat more effective although for this condition of test all of the strengths were low, as will be seen from the values in the following table:

Conditions of Test	Compressive Strength, lb. per sq. in.			
	2 days	7 days	28 days	3 months
Specimens made in laboratory, cured in moist room:				
0 per cent calcium chloride	410	1230	2640	4620
3 " " "	600	1260	2320	3670
Specimens made in laboratory, cured outdoors:				
0 per cent calcium chloride	100	430	1670	2930
3 " " "	200	750	1820	2670
Specimens made outdoors, cured in moist room:				
0 per cent calcium chloride	180	960	2680	4410
3 " " "	380	1010	2160	3440
Specimens made outdoors, cured outdoors:				
0 per cent calcium chloride	45	300	1660	2820
3 " " "	185	710	1980	2900

Table IX shows that the temperature of the concrete made and cured outdoors was not appreciably affected by the addition of calcium chloride.

Salts added to mixing water in freezing weather have two very different functions:

1. To depress the freezing point of the water slightly;
2. To accelerate the early hardening of the concrete with accompanying rise in temperature due to chemical reaction.

The following table shows the effect of certain percentages of common salt and calcium chloride on the freezing point of water:

Solution, per cent by weight	Freezing Point, deg. Fahr.	
	Common Salt	Calcium Chloride
0	32.0	32.0
1	30.5	31.1
2	29.3	30.4
5	25.2	27.7
10	18.7	21.4
15	6.1	−1.5

Five per cent of common salt lowers the freezing point about 6° F. However, tests made in this laboratory, reported elsewhere,[1] have shown that 5 per cent of common salt reduces the compressive strength of the concrete at 28 days about 30 per cent, and in the preceding discussion it has been shown that more than about 6 per cent of calcium chloride gives strengths below normal. It is evident, therefore, that dependence should not be placed on the lowered freezing point of the mixing water. In cold-weather work it is much more desirable to heat the materials and furnish proper protection and artificial heat to the structure, than to depend on chemical admixtures in the concrete.

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[1] Duff A. Abrams, "Tests of Impure Waters for Mixing Concrete," *Proceedings*, Am. Concrete Inst. (1924).

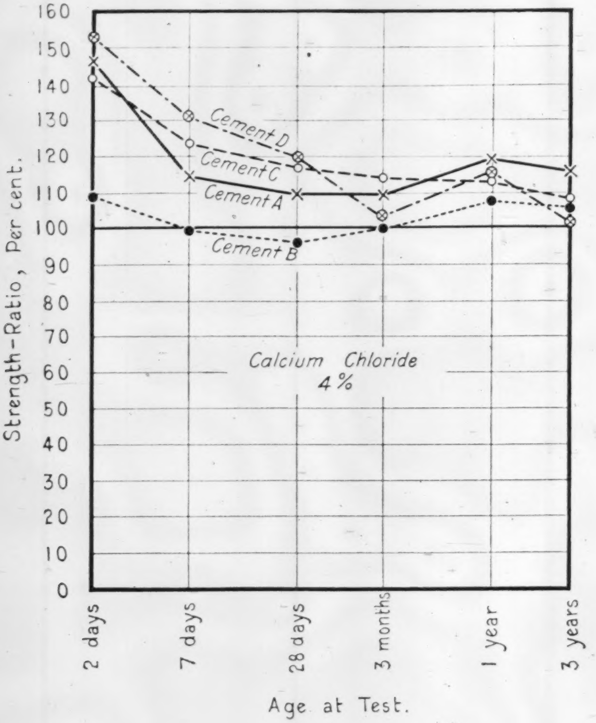

FIG. 11.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Brand of Cement.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Age plotted to logarithmic scale.
Mix 1:5.2 by volume; relative consistency 1.00.
Calcium chloride *B* was used.
Data from Table VII.

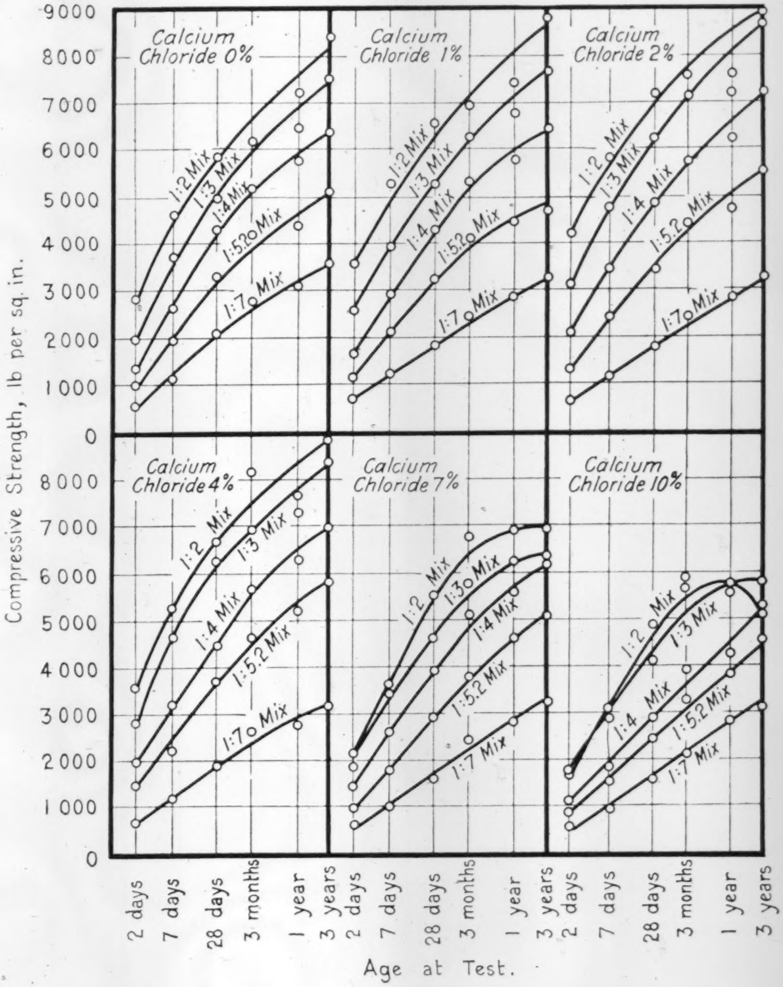

FIG. 12.—Effect of Age on the Strength of Concrete.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Age plotted to logarithmic scale.
Relative consistency 1.00.
Calcium chloride *B* was used.
Each value is the average of 5 tests made on different days.
Data from Table III; compare Figs. 13, 14, and 15.

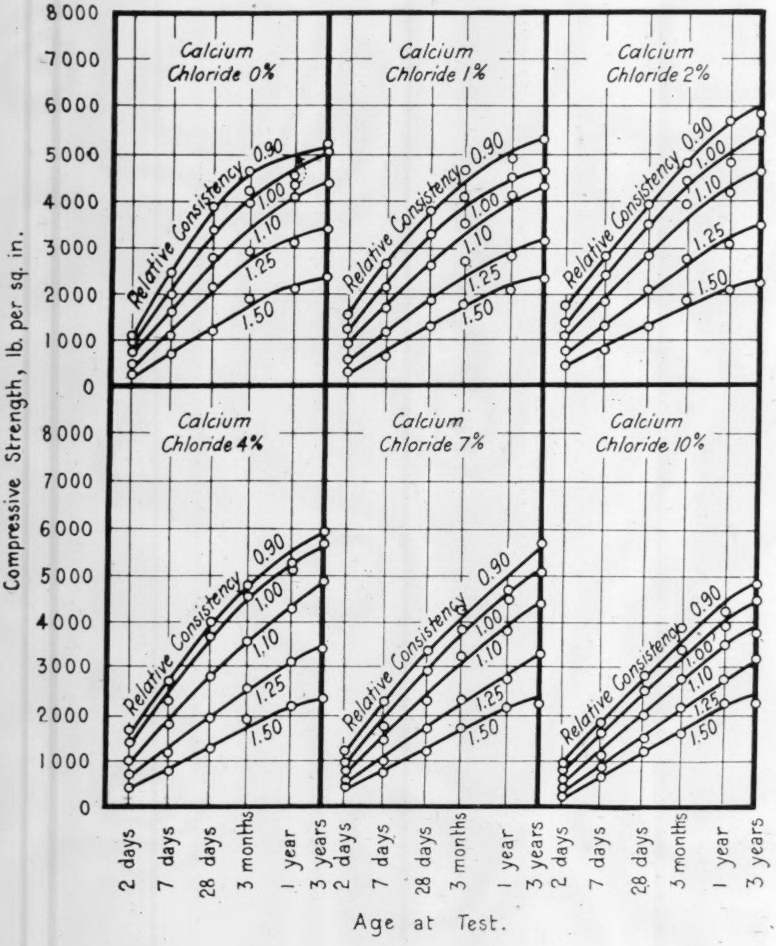

FIG. 13.—Effect of Age on the Strength of Concrete.

Compression tests of 6 by 12-in concrete cylinders cured in moist room.
Age plotted to logarithmic scale.
Mix 1: 5.2 by volume.
Calcium chloride *B* was used.
Each value is the average of 5 tests made on different days.
Data from Table IV; compare Figs. 12, 14, and 15.

Effect of Calcium Chloride as Influenced by Brand of Cement.—Calcium chloride *B* was used in parallel tests of concrete made from different brands of portland cement (A, B, C, D) in both Series 156 and 158; in Series 158 "Laboratory" cement made up of a mixture of equal parts of the same brands was also used. The two series of tests were made from different lots of cements. In general tests were made at ages of 2 days to 3 years. In Series 156 tests were made for 0 and 4 per cent of calcium chloride for moist-room curing (See Tables VII and XI and Fig. 11). In Series 158, calcium chloride was used in quantities ranging from 0 to 10 per cent by weight of cement for concrete cured 14 days in moist room, remainder in air of laboratory (See Tables VIII and XI).

The miscellaneous tests and chemical analyses of the cements are given in Tables XIII and XV.

Cements A, C and D and laboratory cement were affected similarly by calcium chloride. The behavior of cement B was somewhat erratic; in Series 156 this cement showed a slight increase in strength at 2 days, 1 and 3 years due to the addition of 4 per cent of calcium chloride and approximately normal strength at all other ages (See Fig. 11). This cement gave average concrete strengths at early ages, but abnormally high strengths at ages of 3 months to 3 years. In Series 158, cement B gave strength-ratios approximately the same as the other brands.

Effect of Calcium Chloride as Influenced by Age at Test.—In all of the tests the relation of age to strength is shown. It is of interest here to consider the influence of the age at test on the action of calcium chloride in concrete.

Fig. 12 gives data showing the relation of strength to age. Separate curves are plotted for each mix and amount of admixture (calcium chloride *B*). Similarly, Fig. 13 shows the data from the tests with varying quantity of mixing water. These curves are typical of all the data from these tests when plotted in the same manner and show that the strength of concrete is approximately proportional to the logarithm of the age at test.

Fig. 14 has been derived from the data of Figs. 12 and 13. It shows a comparison of the age-strength relation of the plain concrete with concrete containing 2 per cent of calcium chloride for three different mixes of normal consistency and for four different consistencies of 1:5.2 mix. The diagrams show clearly the important fact that for all but the lean and wetter mixes the increase in strength produced by the addition of 2 per cent of calcium chloride when expressed in *pounds per square inch* was approximately constant for all ages of

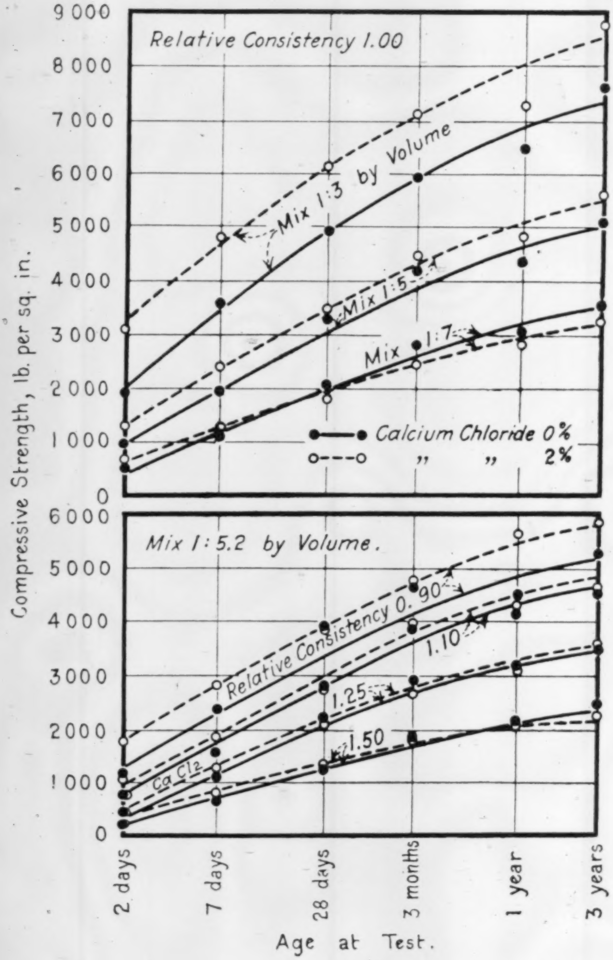

FIG. 14.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Age at Test.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Age plotted to logarithmic scale.
Calcium chloride *B* was used.
Each value is the average of 5 tests made on different days.
Data from Tables III and IV; compare Figs. 12, 13 and 15.

test. It is evident that the effect of calcium chloride is to produce an increase in strength at the early ages which is maintained throughout the later periods of test.

The following table gives the compressive strength of 1:5.2 concrete for relative consistency 1.00 at different ages (See Table I). The difference between the plain and treated concrete was approximately constant at all ages and averaged 400 lb. per sq. in.

Age at Test	Compressive Strength of Concrete, lb. per sq. in.			Strength-Ratios in terms of strength at 28 days, per cent	
	Plain	2 per cent Calcium Chloride, Average *A* and *B*	Difference	Plain	2 per cent Calcium Chloride
2 days	950	1400	450	29	40
7 days	1940	2410	470	59	68
28 days	3310	3530	220	100	100
3 months	4170	4460	290	126	127
1 year	4320	4850	530	131	138
3 years	5020	5470	450	152	155
			Av. 400		

It is interesting to note that the ratios of the strength at different ages to the 28-day strength for both plain concrete and concrete with 2 per cent of calcium chloride were essentially the same at ages greater than 28 days. At ages of 2 and 7 days, the treated specimens show a higher ratio to the 28-day strength than the plain.

Fig. 15 shows the variation of strength-ratios with age for three percentages of different types of admixtures. In general these include the optimum percentage. an intermediate percentage and the maximum percentage used. The strength-ratio was a maximum at the 2-day period in all cases, and decreased with age. The strength-ratios for the optimum percentage decreased more rapidly than for the less effective percentages. This decrease in strength-ratios is explained by the fact that the additional strength in pounds per square inch due to admixtures is approximately constant at all ages, so that when compared to the strength of the plain concrete which is increasing with age, the resulting strength-ratios become smaller.

Mortar Tests.—Tests of a 1: $2\frac{1}{2}$ mix by volume using sand graded up to the No. 4 sieve were made at ages of 2 days to 3 years (See Tables II, VII and X). At ages of 2 and 7 days the mortar tests gave essentially the same results as the concrete when admixtures of calcium chloride type were used. However, at the later ages the results were somewhat erratic. For example, calcium chloride *B* showed strength-ratios as low as 80 to 90 per cent. Specimens could not be

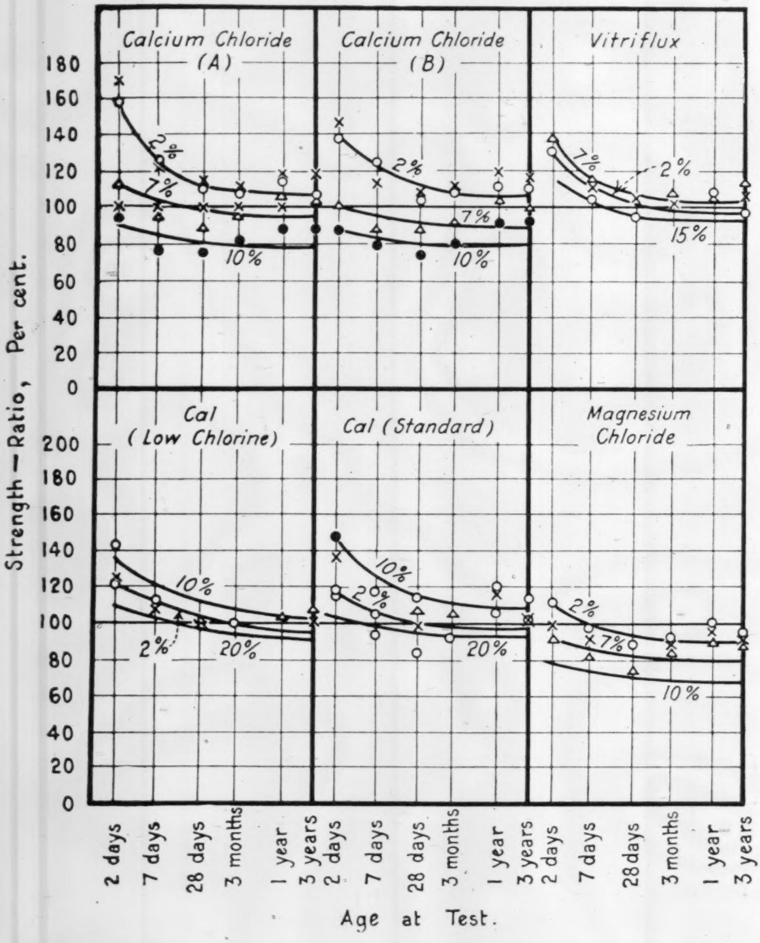

FIG. 15.—Effect of Different Admixtures on the Strength of Concrete as Influenced by Age at Test.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Age plotted to logarithmic scale.
Mix 1:5.2; relative consistency 1.00.
Each value is the average of 4 to 10 tests made on different days.
Data from Table I; compare Figs. 12, 13, 14 and 16.

made for calcium chloride (either *A* or *B*) for percentages of 7 per cent and higher due to the quick stiffening of the mortar.

Magnesium chloride showed an increase in strength in the mortar specimens at all ages as contrasted with the decrease in the case of the concrete specimens for ages greater than 7 days.

MISCELLANEOUS TESTS

Effect of Calcium Chloride on Plasticity of Concrete.—The proper quantity of mixing water or mixing solution was used in each case to produce concrete of the same plasticity as measured by the flow table. The plasticity of the concrete as measured by the flow and the corresponding water-ratios, are given in Table XII. The admixtures affected the quantity of water required to produce a constant flow only in so far as they caused the concrete to stiffen more quickly. Their effect, therefore, depended largely on the rapidity with which the flow test was carried out. In the case of the calcium chloride solutions the same quantity of mixing water was required to produce the same apparent plasticity and the same flow except in a few instances for the higher percentages where the concrete stiffened so rapidly that the values of the flow were erratic. For the magnesium chloride and Cal the quantity of mixing water required to maintain constant flow increased with the percentage of admixture. In the case of the Cal this was probably due to the fact that it contained considerable fine material (hydrated lime). It is not clear from the data of the flow tests or the time-of-setting tests why additional water was required for magnesium chloride and not for calcium chloride.

Normal Consistency.—The water required to produce normal consistency was determined for cement A in Series 156 when mixed with different percentages of admixtures. Normal consistency for the cement without admixtures required 23 per cent of water (See Table XIV). For 1 per cent of calcium chloride, in terms of the weight of the cement, 22 per cent of water was required to give normal consistency; with 2 per cent of calcium chloride about the same percentage was required as for cement without admixtures; with 4 per cent of calcium chloride 25 per cent of water was required. Tests could not be made for higher percentages on account of flash set. The water required for normal consistency increased with the addition of Cal for all percentages used in these tests. The behavior of low-chlorine and standard Cal was essentially the same.

Vitriflux gave about the same results as calcium chloride in proportion to the amount of chlorine present.

Magnesium chloride also gave values approximately the same as calcium chloride except that higher percentages could be used without producing flash set.

Time of Setting.—Data on the time of setting of cement A using the different admixtures are shown in Table XIV. In general the time of setting was shortened by all of the admixtures. Calcium chloride A and B gave about the same results. For the percentage found to give best results in concrete (2 per cent) the time of final set was reduced from 3½ to about 2 hours as determined with the Vicat needle, and from 5½ to about 3 hours for the Gillmore needle.

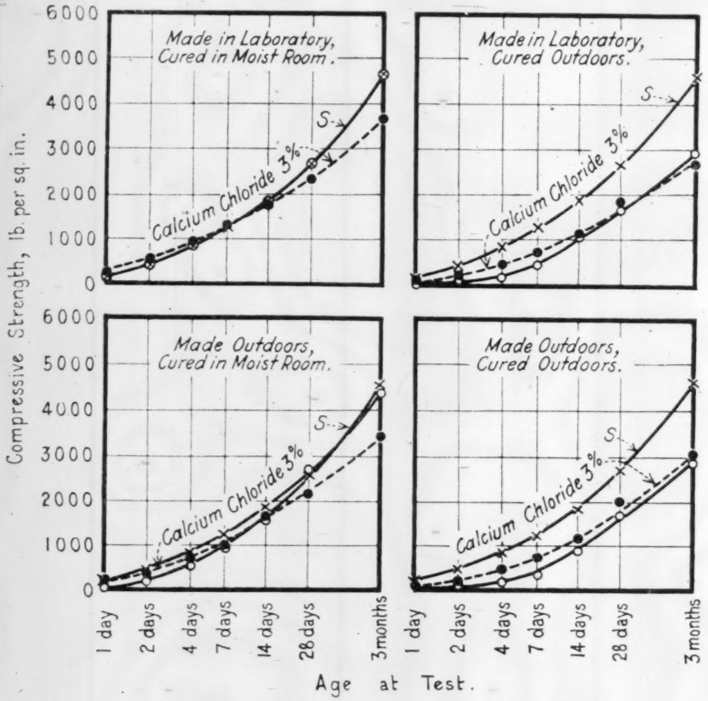

FIG. 16.—Tests of Concrete Made and Cured at Low Temperatures.

Compression tests of 6 by 12-in. concrete cylinders.
Age potted to logarithmic scale.
Mix 1:5 by volume; relative consistency 1.25.
Calcium chloride *A* was used.
Each value is the average of 6 tests made on different days.
Data from Table IX.
Curve *S* repeated on each diagram for comparison.

With 7 per cent of Vitriflux, the optimum percentage in concrete, final set was attained in about 1½ hours. With Cal of low chlorine content, 10 per cent gave a final set at about 2 hours. No time-of-setting tests were made with standard Cal. Flash set was produced by additions of calcium chloride greater than 4 per cent and for magnesium chloride and Vitriflux for additions greater than 7 per cent.

Soundness.—Table XIV gives data of standard soundness tests on cement A using the various admixtures. In all cases the cement passed the test satisfactorily.

Bibliography.—The attached bibliography lists the more important papers which contain information on the effect of calcium chloride as an admixture in cement and concrete.

The brief notes which accompany many of the references are meant to reflect the views expressed in the paper and do not indicate the opinion of the author of this report.

Related Tests.—We are now conducting field and laboratory experiments on the use of calcium chloride and other compounds as curing agents for concrete roads. Part of these tests are being made at Sacramento in cooperation with the California Highway Commission. This work will furnish the subject matter of a separate report.

A comprehensive report was recently published on tests of impure waters for mixing concrete. (*Proceedings*, American Concrete Institute, 1924, reprinted as Bulletin 12 of the Structural Materials Research Laboratory.) This report gives tests of concrete mixed with sulfate waters and solutions of common salt.

CONCLUSIONS

The principal conclusions from these tests are:

1. Calcium chloride and the admixtures containing calcium chloride when used within certain limiting percentages, gave increased strength to concrete.

2. Magnesium chloride in flake form (46 per cent magnesium chloride, 54 per cent water) when used in concrete caused a reduction in strength except for small percentages, which showed a slight increase for 2 and 7-day tests.

3. The effect of the calcium-chloride admixtures in concrete varied with the type and quantity of admixture. When the tests are compared on the basis of chlorine content the different admixtures give similar results but not the same numerical values.

4. Calcium-chloride admixtures of the types used increased the strength of concrete approximately in proportion to the amount used up to a certain "optimum" percentage; the strength increase became less for further additions. Beyond a certain "critical" percentage

further additions produced a reduction in strength as compared to similar concrete without admixtures.

5. Optimum and critical percentages for the calcium chloride admixtures used in these tests for 1:5.2 concrete of normal consistency and cured in moist room, were as follows:

Admixture	Per Cent of Admixture by Weight of Cement		Per Cent of Chlorine by Weight of Cement	
	Optimum	Critical	Optimum	Critical
Commercial Calcium Chloride A	2 to 4	6 to 8	1 to 2	3 to 4
Commercial Calcium Chloride B	2 to 4	6 to 8	1 to 2	3 to 4
Standard Cal	7 to 10	15 to 20	1 to 2	3 to 4
Low-Chlorine Cal	about 10	15 to 20	1 to 2	2 to 3
Vitriflux	6 to 8	10 to 15	1 to 2	2 to 3

6. The relative effectiveness of the different admixtures when compared on the basis of strength-ratio (the ratio of the strength of concrete containing admixture to that of similar concrete without admixture, expressed as a percentage) for the optimum percentages, is shown by the following strength-ratios, which are based on tests of 1:5.2 concrete of normal consistency cured in the moist room:

Admixture	Strength-Ratio for Optimum Percentage					
	2 days	7 days	28 days	3 mo.	1 yr.	3 yr.
Commercial Calcium Chloride A	170	125	110	112	117	118
Commercial Calcium Chloride B	147	124	109	109	119	116
Standard Cal	151	123	107	107	121	119
Low-Chlorine Cal	143	118	101	104	113	111
Vitriflux	138	115	106	108	109	114

7. The addition of calcium-chloride admixtures in amounts less than the "critical" percentage produced an increase in concrete strength that was practically constant at all ages. This constant strength increase, when expressed as a percentage of the strength of concrete without admixture, showed a diminishing ratio as the concrete gained in strength with age.

8. The addition of 2 per cent of calcium chloride to 1:5.2 concrete of the consistency ordinarily used in construction work (1.10 to 1.25) produced an increase in compressive strength of 100 to 200 lb. per sq. in. at ages of 2 days to 3 years; for 1.50 consistency there was little or no increase; for consistency 0.90 the increase was about 550 lb. per sq. in.

9. The increase in strength due to the addition of 2 per cent of commercial calcium chloride was practically negligible for a 1:7 mix; it increased with the cement content up to about a 1:4 mix; for mixes

richer than 1:4 the strength increase remained about the same. The strength increase for the different mixes and the corresponding strength-ratios for ages of 2 days to 3 years were as follows:

Mix	Strength Increase, lb. per sq. in. (same for all ages)	Strength-Ratio, per cent (Fig. 4)				
		2 days	7 days	28 days	3 mo.	3 yr.
1:7.....	Negligible (±100)	115	107	85	88	95
1:5.2...	400	138	125	107	110	110
1:4.....	700	148	130	119	117	115
1:3.....	1200	150	130	122	119	115
1:2.....	1300	149	130	122	120	105

10. The tests confirm the relation between water-cement ratio and compressive strength pointed out in other publications of this Laboratory. The water-ratio-strength curves for 2 per cent of commercial calcium chloride were similar in form to those for plain concrete but divergent at the lower water-ratios, showing the greater effect of the calcium chloride on the richer mixes and drier concretes.

11. The effect of commercial calcium chloride on the strength of concrete cured under different moisture conditions at normal temperatures was slightly greater in concrete cured in the air of the laboratory than in concrete cured in water or in the moist room.

12. For concrete cured outdoors at temperatures near freezing, the use of 3 per cent of calcium chloride produced about the same strength increase as for other curing conditions. This strength increase appears as a much higher percentage gain when compared to the low strengths attained for outdoor curing. Too much dependence should not be placed on the use of calcium chloride for preventing freezing of concrete in cold weather; common salt should not be used for this purpose.

13. The cements used in the tests were in general similarly affected by addition of calcium chloride.

14. The effect of calcium chloride in mortar was essentially the same as in concrete.

15. The time of setting of the cement used was shortened by each of the admixtures. Flash set was produced by most of the admixtures when used in percentages somewhat in excess of those found to give greatest strength increases in concrete.

16. The important conclusion from these tests may be summarized as follows:

In the use of calcium chloride no advantage was gained for percentages of the commercial product greater than 2 or 3 per cent of the weight of cement; (chlorine content 1 to $1\frac{1}{2}$ per cent). This amount when used in mixes of about 1:5 and in consistencies suitable for building construction showed an increase in compressive strength of from 100 to 200 lb. per sq. in. which increase was practically constant at ages of 2 days to 3 years. For richer mixes and drier consistencies the strength increase was greater and for leaner mixes and wetter concretes it was less.

TABLE I.—EFFECT OF TYPE OF ADMIXTURE ON THE STRENGTH OF CONCRETE—SERIES 156.

Compression tests of 6 by 12-in. concrete cylinders.
Mix 1:5.2 by volume (1:2:4).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Cement: portland cement "A" purchased in Chicago.
Relative consistency 1.00 (Flow about 180, see Table XII).
Specimens cured in moist room until test; tested damp.
Each value is the average of from 4 to 10 tests made on different days unless otherwise noted.
Strength-ratios are percentages of the strength of concrete at same age without admixture.
Admixtures and chlorine expressed as per cent of weight of cement.
Data plotted in Figs. 1 and 2.

Admixture, per cent	Calcium Chloride *A*			Calcium Chloride *B*			Cal						Vitriflux			Magnesium Chloride		
							Low Chlorine			Standard								
	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
2-DAY TESTS																		
0[a]	0	950	100	0	950	100	0	950	100	0	950	100	0	950	100	0	950	100
1	0.5	1220	128	0.5	1220	128	0.1	....	...	...	....	...	0.2	1220	128	0.3	1090	115
2	1.0	1500	158	1.0	1310	138	0.2	1150	121	0.3	1120	118	0.4	1230	130	0.7	1060	111
4	1.9	1610	170	1.9	1400	147	0.4	1170	123	0.6	1300	137	0.9	1310	138	1.4	940	99
7	3.3	1070	113	3.4	960	101	0.7	1280	135	1.1	1430	151	1.5	1310	138	2.4	860	91
10	4.8	890	94	4.8	830	87	1.1	1360	143	1.6	1410	148	2.1	1230	130	3.4	700	74
15	...	....	...	...	....	...	1.6	1230	130	2.4	1230	129	3.2	1090	115	...	....	...
20	...	....	...	...	....	...	2.1	1100	116	3.2	1090	115	...	....	...	...	....	...
7-DAY TESTS																		
0[a]	0	1940	100	0	1940	100	0	1940	100	0	1940	100	0	1940	100	0	1940	100
1	0.5	2220	114	0.5	2120	109	0.1	....	...	...	....	...	0.2	2090	108	0.3	1970	102
2	1.0	2420	125	1.0	2400	124	0.2	2180	112	0.3	2060	106	0.4	2040	105	0.7	1880	97
4	1.9	2380	123	1.9	2220	114	0.4	2100	108	0.6	2280	118	0.9	2200	113	1.4	1800	93
7	3.3	1820	94	3.4	1700	88	0.7	2240	115	1.1	2390	123	1.5	2240	115	2.4	1580	81
10	4.8	1490	77	4.8	1560	80	1.1	2290	118	1.6	2260	117	2.1	2080	107	3.4	1380	71
15	...	....	...	...	....	...	1.6	2100	108	2.4	2130	110	3.2	1810	93	...	....	...
20	...	....	...	...	....	...	2.1	1830	94	3.2	1820	94	...	....	...	...	....	...
28-DAY TESTS																		
0[a]	0	3310	100	0	3310	100	0	3310	100	0	3310	100	0	3310	100	0	3310	100
1	0.5	3230	98	0.5	3240	98	0.1	....	...	...	....	...	0.2	3220	97	0.3	3090	94
2	1.0	3630	110	1.0	3430	104	0.2	3310	100	0.3	3070	93	0.4	3150	95	0.7	2920	88
4	1.9	3620	109	1.9	3620	109	0.4	3330	100	0.6	3320	100	0.9	3500	106	1.4	2780	84
7	3.3	2950	89	3.4	2890	87	0.7	3340	101	1.1	3550	107	1.5	3490	105	2.4	2450	74
10	4.8	2520	76	4.8	2460	74	1.1	3300	100	1.6	3540	107	2.1	3140	95	3.4	2120	64
15	...	....	...	...	....	...	1.6	3200	97	2.4	3100	94	3.2	3010	91	...	....	...
20	...	....	...	...	....	...	2.1	2910	88	3.2	2770	84	...	....	...	...	....	...
3-MONTH TESTS																		
0[a]	0	4170	100	0	4170	100	0	4170	100	0	4170	100	0	4170	100	0	4170	100
1	0.5	4160	100	0.5	4060	97	0.1	....	...	...	....	...	0.2	4210	101	0.3	3980	95
2	1.0	4450	107	1.0	4470	107	0.2	4130	99	0.3	4050	97	0.4	4110	99	0.7	3800	91
4	1.9	4670	112	1.9	4550	109	0.4	4190	101	0.6	4390	105	0.9	4260	102	1.4	3650	88
7	3.3	3980	95	3.4	3780	91	0.7	4260	102	1.1	4430	106	1.5	4500	108	2.4	3400	82
10	4.8	3330	80	4.8	3320	80	1.1	4330	104	1.6	4460	107	2.1	4040	97	3.4	2840	68
15	...	....	...	...	....	...	1.6	4160	100	2.4	4180	100	3.2	3800	91	...	....	...
20	...	....	...	...	....	...	2.1	3900	94	3.2	3840	92	...	....	...	...	....	...
1-YEAR TESTS																		
0[a]	0	4320	100	0	4320	100	0	4320	100	0	4320	100	0	4320	100	0	4320	100
1	0.5	4340	100	0.5	4480	104	0.1	....	...	...	....	...	0.2	4380	101	0.3	4100	95
2	1.0	4900	114	1.0	4790	111	0.2	4370	101	0.3	4590	106	0.4	4730	109	0.7	4320	100
4	1.9	5060	117	1.9	5130	119	0.4	4460	103	0.6	5000	116	0.9	4720	109	1.4	4160	96
7	3.3	4630	107	3.4	4510	104	0.7	4460	103	1.1	5190	120	1.5	4640	107	2.4	3870	90
10	4.8	3810	88	4.8	3870	90	1.1	4880	113	1.6	5220	121	2.1	4640	107	3.4	3250	75
15	...	....	...	...	....	...	1.6	4610	107	2.4	4730	109	3.2	4580	106	...	....	...
20	...	....	...	...	....	...	2.1	4450	103	3.2	4510	104	...	....	...	...	....	...
3-YEAR TESTS																		
0[a]	0	5020	100	0	5020	100	0	5020	100	0	5020	100	0	5020	100	0	5020	100
1	0.5	5170	103	0.5	4680	93	0.1	....	...	...	....	...	0.2	4940	98	0.3	4710	94
2	1.0	5400	108	1.0	5540	110	0.2	5130	102	0.3	5140	102	0.4	4940	98	0.7	4830	96
4	1.9	5900	118	1.9	5840	116	0.4	5050	101	0.6	5100	102	0.9	5330	106	1.4	4650	93
7	3.3	5210	104	3.4	5040	100	0.7	5440	108	1.1	5980	119	1.5	5710	114	2.4	4500	90
10	4.8	4490	89	4.8	4590	91	1.1	5340	106	1.6	5750	115	2.1	5510	110	3.4	3950	79
15	...	....	...	...	....	...	1.6	5550	111	2.4	5270	105	3.2	5360	107	...	....	...
20	...	....	...	...	....	...	2.1	5330	106	3.2	5050	101	...	....	...	...	....	...

[a] All values average of 25 tests.

TABLE II.—EFFECT OF TYPE OF ADMIXTURE ON THE STRENGTH OF MORTAR—SERIES 156.

Compression tests of 2 by 4-in. mortar cylinders.
Mix 1:2.5 by volume.
Aggregate: sand from Elgin, Ill., graded 0 to No. 4.
Cement: portland cement "A" purchased in Chicago.
Relative consistency 1.00 (Flow about 130, see Table XII).
Specimens cured in water until test; tested damp.
Each value is the average of 5 tests made on different days unless otherwise noted.
Strength-ratios are percentages of strength of mortar at same age without admixture.
Admixture and chlorine expressed as per cent of weight of cement.

Admixture, per cent	Calcium Chloride *A*			Calcium Chloride *B*			Cal						Vitriflux			Magnesium Chloride		
							Low Chlorine			Standard								
	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
2-DAY TESTS																		
0[a]	0	1970	100	0	1970	100	0	1970	100	0	1970	100	0	1970	100	0	1970	100
1	0.5	2710	138	0.5	2500	127	0.1	...	...	...	...	...	0.2	2490	126	0.3	2350	119
2	1.0	2880	146	1.0	2550	130	0.2	2230	113	0.3	2730	139	0.4	2650	135	0.7	2590	131
4	1.9	2610	132	1.9	2290	116	0.4	2530	128	0.6	2910	148	0.9	2920	148	1.4	2260	115
7	...	[b]	...	...	[b]	...	0.7	2680	136	1.1	3190	162	1.5	2580	131	2.4	2010	102
10	...	...	...	...	...	...	1.1	2730	139	1.6	2950	150	2.1	2370	120	...	[b]	...
15	...	...	...	...	...	...	1.6	2580	131	2.4	2770	141	...	[b]	...	...	...	...
20	...	...	...	...	...	...	2.1	2370	120	3.2	2420	123	...	...	...	...	...	...
7-DAY TESTS																		
0[a]	0	3610	100	0	3610	100	0	3610	100	0	3610	100	0	3610	100	0	3610	100
1	0.5	3800	105	0.5	3960	110	0.1	...	...	...	...	...	0.2	3610	100	0.3	3750	104
2	1.0	4320	120	1.0	3920	109	0.2	3560	99	0.3	4210	117	0.4	3970	110	0.7	4040	112
4	1.9	3900	108	1.9	3640	101	0.4	3950	109	0.6	4580	127	0.9	4620	128	1.4	4000	111
7	...	[b]	...	...	[b]	...	0.7	4080	113	1.1	4930	136	1.5	4410	122	2.4	3430	95
10	...	...	...	...	...	...	1.1	4480	124	1.6	4730	131	2.1	3840	106	...	[b]	...
15	...	...	...	...	...	...	1.6	4090	113	2.4	3500	97	...	[b]	...	...	...	...
20	...	...	...	...	...	...	2.1	3500	97	3.2	3260	90	...	...	...	...	...	...
28-DAY TESTS																		
0[a]	0	5100	100	0	5100	100	0	5100	100	0	5100	100	0	5100	100	0	5100	100
1	0.5	5400	106	1.5	5020	98	0.1	...	...	...	...	...	0.2	5450	107	0.3	5070	99
2	1.0	5560	109	1.0	5010	98	0.2	5330	105	0.3	5470	107	0.4	5700	112	0.7	5410	106
4	1.9	5250	103	1.9	4570	90	0.4	5450	107	0.6	5940	116	0.9	5800	114	1.4	5490	108
7	...	[b]	...	...	[b]	...	0.7	5440	107	1.1	6200	122	1.5	5460	107	2.4	4770	94
10	...	...	...	...	...	...	1.1	5390	106	1.6	5400	106	2.1	4700	92	...	[b]	...
15	...	...	...	...	...	...	1.6	5190	102	2.4	5540	109	...	[b]	...	...	...	...
20	...	...	...	...	...	...	2.1	4960	97	3.2	4700	92	...	...	...	...	...	...
3-MONTH TESTS																		
0[a]	0	6080	100	0	6080	100	0	6080	100	0	6080	100	0	6080	100	0	6080	100
1	0.5	5580	92	0.5	5740	94	0.1	...	...	...	...	...	0.2	5750	94	0.3	6310	104
2	1.0	6490	107	1.0	5790	95	0.2	6030	99	0.3	6390	105	0.4	5230	86	0.7	6700	110
4	1.9	6010	99	1.9	5180	85	0.4	6490	107	0.6	7030	116	0.9	6550	108	1.4	6470	106
7	...	[b]	...	...	[b]	...	0.7	6470	106	1.1	7420	122	1.5	6550	108	2.4	5950	98
10	...	...	...	...	...	...	1.1	6320	104	1.6	6810	112	2.1	4820	79	...	[b]	...
15	...	...	...	...	...	...	1.6	6350	104	2.4	6250	103	...	[b]	...	...	...	...
20	...	...	...	...	...	...	2.1	5800	95	3.2	4960	81	...	...	...	...	...	...
1-YEAR TESTS																		
0[a]	0	6520	100	0	6520	100	0	6520	100	0	6520	100	0	6520	100	0	6520	100
1	0.5	5840	90	0.5	6410	98	0.1	...	...	...	...	...	0.2	6540	100	0.3	7510	115
2	1.0	6930	106	1.0	6110	94	0.2	6550	100	0.3	7130	109	0.4	6640	102	0.7	6940	106
4	1.9	5800	89	1.9	5300	81	0.4	6710	103	0.6	7750	119	0.9	7050	108	1.4	7110	109
7	...	[b]	...	...	[b]	...	0.7	6150	94	1.1	7900	121	1.5	6630	102	2.4	6180	95
10	...	...	...	...	...	...	1.1	7880	121	1.6	7150	109	2.1	5600	86	...	[b]	...
15	...	...	...	...	...	...	1.6	6880	105	2.4	6760	104	...	[b]	...	...	...	...
20	...	...	...	...	...	...	2.1	6510	100	3.2	6670	102	...	...	...	...	...	...
3-YEAR TESTS																		
0[a]	0	6820	100	0	6820	100	0	6820	100	0	6820	100	0	6820	100	0	6820	100
1	0.5	7240	106	0.5	6430	94	0.1	...	...	...	...	...	0.2	7030	103	0.3	7480	110
2	1.0	5440	80	1.0	6560	96	0.2	6220	91	0.3	7630	112	0.4	6950	102	0.7	7180	105
4	1.9	5870	86	1.9	5590	82	0.4	6050	89	0.6	7980	117	0.9	6640	97	1.4	6920	102
7	...	[b]	...	...	[b]	...	0.7	6700	98	1.1	8840	130	1.5	6490	95	2.4	7250	106
10	...	...	...	...	...	...	1.1	7360	108	1.6	8770	129	2.1	6030	89	...	[b]	...
15	...	...	...	...	...	...	1.6	6660	98	2.4	7590	111	...	[b]	...	...	...	...
20	...	...	...	...	...	...	2.1	7230	106	3.2	6940	102	...	...	...	...	...	...

[a] All values average of 15 tests.

[b] Unable to make specimens with higher percentages due to quick stiffening.

TABLE III.—EFFECT OF CALCIUM CHLORIDE ON THE STRENGTH OF CONCRETE AS INFLUENCED BY MIX—SERIES 156.

Compression tests of 6 by 12-in. concrete cylinders.
Mix by volume.
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Cement: portland cement "A" purchased in Chicago.
Relative consistency 1.00 (Flow about 180, see Table XII).
Specimens cured in moist room until test; tested damp.
Each value is the average of 5 tests made on different days unless otherwise noted.
Strength-ratios are percentages of the strength of concrete at same age without calcium chloride.
Data plotted in Figs. 3, 4, 6, 12 and 14.

Calcium Chloride *B*, per cent	Chlorine, per cent[a]	Mix 1:7			Mix 1:5.2			Mix 1:4			Mix 1:3			Mix 1:2		
		CaCl₂[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	CaCl₂[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	CaCl₂[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	CaCl₂[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	CaCl₂[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
2-DAY TESTS																
0.......	0	0	540	100	0	950[c]	100	0	1350	100	0	1960	100	0	2780	100
1.......	0.5	1.4	630	117	1.8	1220[d]	128	2.0	1660	123	2.3	2510	128	3.1	3520	126
2.......	1.0	2.7	620	115	3.7	1310[d]	138	4.3	2010	149	5.3	3110	159	6.4	4150	149
4.......	1.9	5.5	650	120	7.8	1400[d]	147	8.9	1960	145	11.0	2790	142	12.9	3550	128
7.......	3.4	10.0	560	104	13.4	960[d]	101	16.5	1480	110	19.9	1920	98	20.2	2020	73
10.......	4.8	14.9	590	109	19.8	830[d]	87	22.5	1040	77	29.5	1740	89	31.6	1670	60
7-DAY TESTS																
0.......	0	0	1100	100	0	1940[c]	100	0	2660	100	0	3680	100	0	4530	100
1.......	0.5	1.4	1140	104	1.8	2120[d]	109	2.0	2970	111	2.3	3920	106	3.1	5290	116
2.......	1.0	2.7	1160	106	3.7	2400[d]	124	4.3	3450	130	5.3	4760	130	6.4	5890	130
4.......	1.9	5.5	1160	106	7.8	2200[d]	114	8.9	3170	119	11.0	4620	125	12.9	5280	116
7.......	3.4	10.0	990	90	13.4	1700[d]	88	16.5	2520	94	19.9	3440	93	20.2	3500	77
10.......	4.8	14.9	930	85	19.8	1560[d]	80	22.5	1780	67	29.5	3030	82	31.6	2820	62
28-DAY TESTS																
0.......	0	0	2060	100	0	3310[c]	100	0	4240	100	0	4920	100	0	5750	100
1.......	0.5	1.4	1780	86	1.8	3240[d]	98	2.0	4210	99	2.3	5200	106	3.1	6500	113
2.......	1.0	2.7	1710	83	3.7	3430[d]	104	4.3	4900	116	5.3	6160	125	6.4	7070	123
4.......	1.9	5.5	1840	89	7.8	3620[d]	109	8.9	4490	106	11.0	6280	128	12.9	6510	113
7.......	3.4	10.0	1650	80	13.4	2890[d]	87	16.5	3960	93	19.9	4510	92	20.2	5400	94
10.......	4.8	14.9	1610	78	19.8	2460[d]	74	22.5	2920	69	29.5	4090	83	31.6	4870	85
3-MONTH TESTS																
0.......	0	0	2790	100	0	4170[c]	100	0	5140	100	0	5960	100	0	6140	100
1.......	0.5	1.4	2490	89	1.8	4060[d]	97	2.0	5280	103	2.3	6220	104	3.1	6910	113
2.......	1.0	2.7	2430	87	3.7	4470[d]	107	4.3	5750	112	5.3	7070	118	6.4	7590	124
4.......	1.9	5.5	2520	90	7.8	4550[d]	109	8.9	5670	110	11.0	6920	116	12.9	8030	131
7.......	3.4	10.0	2400	86	13.4	3780[d]	91	16.5	5050	98	19.9	5700	96	20.2	6740	110
10.......	4.8	14.9	2180	78	19.8	3320[d]	80	22.5	3980	77	29.5	5670	95	31.6	5800	95
1-YEAR TESTS																
0.......	0	0	3050	100	0	4320[c]	100	0	5750	100	0	6490	100	0	7090	100
1.......	0.5	1.4	2810	92	1.8	4480[d]	104	2.0	5790	101	2.3	6730	104	3.1	7410	105
2.......	1.0	2.7	2870	94	3.7	4790[d]	111	4.3	6340	110	5.3	7270	112	6.4	7570	106
4.......	1.9	5.5	2730	90	7.8	5130[d]	119	8.9	6260	109	11.0	7320	113	12.9	7620	107
7.......	3.4	10.0	2840	93	13.4	4510[d]	104	16.5	5650	98	19.9	6240	96	20.2	6820	96
10.......	4.8	14.9	2810	92	19.8	3870[d]	90	22.5	4300	75	29.5	5690	88	31.6	5530	78
3-YEAR TESTS																
0.......	0	0	3500	100	0	5020[c]	100	0	6390	100	0	7530	100	0	8390	100
1.......	0.5	1.4	3360	96	1.8	4680[d]	93	2.0	6490	102	2.3	7840	104	3.1	8870	106
2.......	1.0	2.7	3240	93	3.7	5540[d]	110	4.3	7210	113	5.3	8710	116	6.4	8940	107
4.......	1.9	5.5	3080	88	7.8	5840[d]	116	8.9	6980	109	11.0	8470	112	12.9	8970	107
7.......	3.4	10.0	3220	92	13.4	5040[d]	100	16.5	6090	95	19.9	6170	82	20.2	6990	83
10.......	4.8	14.9	3020	86	19.8	4590[d]	91	22.5	5360	84	29.5	5850	78	31.6	5160	62

[a] Per cent of weight of cement.
[b] Per cent of weight of mixing water using commercial product.
[c] Average of 25 tests.
[d] Average of 10 tests.

TABLE IV.—EFFECT OF CALCIUM CHLORIDE ON THE STRENGTH OF CONCRETE AS INFLUENCED BY CONSISTENCY—SERIES 156.

Compression tests of 6 by 12-in. concrete cylinders.
Mix 1:5.2 by volume (1:2:4).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Cement: portland cement "A" purchased in Chicago.
Specimens cured in moist room until test; tested damp.
Each value is the average of 5 tests made on different days unless otherwise noted.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.
Data plotted in Figs. 5, 6, 13 and 14.

Calcium Chloride *B*, per cent[a]	Chlorine, per cent[a]	Relative Consistency of Concrete														
		0.90			1.00			1.10			1.25			1.50[e]		
		$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
2-DAY TESTS																
0	0	0	1110	100	0	950[c]	100	0	720	100	0	440	100	0	280	100
1	0.5	2.0	1540	139	1.8	1220[d]	128	1.6	920	128	1.4	560	127	1.2	360	128
2	1.0	4.0	1700	153	3.7	1310[d]	138	3.2	1040	144	2.9	700	159	2.4	410	146
4	1.9	8.1	1610	145	7.8	1400[d]	147	6.6	980	136	5.8	670	152	4.8	400	143
7	3.4	14.7	1190	107	13.4	960[d]	101	11.8	780	108	10.4	510	116	8.5	400	143
10	4.8	21.5	940	85	19.8	830[d]	87	17.3	590	82	15.1	430	98	12.4	360	128
7-DAY TESTS																
0	0	0	2370	100	0	1940[c]	100	0	1560	100	0	1070	100	0	640	100
1	0.5	2.0	2590	109	1.8	2120[d]	109	1.6	1630	104	1.4	1150	107	1.2	670	105
2	1.0	4.0	2750	116	3.7	2400[d]	124	3.2	1790	115	2.9	1250	117	2.4	780	122
4	1.9	8.1	2660	112	7.8	2220[d]	114	6.6	1770	113	5.8	1150	107	4.8	780	122
7	3.4	14.7	2250	95	13.4	1700[d]	88	11.8	1370	88	10.4	930	87	8.5	720	112
10	4.8	21.5	1780	75	19.8	1560[d]	80	17.3	1100	70	15.1	820	77	12.4	630	98
28-DAY TESTS																
0	0	0	3830	100	0	3310[c]	100	0	2750	100	0	2100	100	0	1200	100
1	0.5	2.0	3740	98	1.8	3250[d]	98	1.6	2580	94	1.4	1810	86	1.2	1270	106
2	1.0	4.0	3830	100	3.7	3430[d]	104	3.2	2710	99	2.9	2020	96	2.4	1280	107
4	1.9	8.1	3850	100	7.8	3620[d]	109	6.6	2770	101	5.8	1830	87	4.8	1260	105
7	3.4	14.7	3310	86	13.4	2890[d]	87	11.8	2290	83	10.4	1700	81	8.5	1210	101
10	4.8	21.5	2770	72	19.8	2460[d]	74	17.3	1980	72	15.1	1570	75	12.4	1200	100
3-MONTH TESTS																
0	0	0	4590	100	0	4170[e]	100	0	3830	100	0	2840	100	0	1860	100
1	0.5	2.0	4610	101	1.8	4060[d]	97	1.6	3490	91	1.4	2660	94	1.2	1720	92
2	1.0	4.0	4670	102	3.7	4470[d]	107	3.2	3860	101	2.9	2680	94	2.4	1800	97
4	1.9	8.1	4780	104	7.8	4550[d]	109	6.6	3490	91	5.8	2510	88	4.8	1850	99
7	3.4	14.7	4200	91	13.4	3780[d]	91	11.8	3220	84	10.4	3250	79	8.5	1690	91
10	4.8	21.5	3810	83	19.8	3320[d]	80	17.3	2640	69	15.1	2080	73	12.4	1580	85
1-YEAR TESTS																
0	0	0	4450	100	0	4320[c]	100	0	4030	100	0	3060	100	0	2080	100
1	0.5	2.0	4730	106	1.8	4480[d]	104	1.6	4030	100	1.4	2800	92	1.2	2030	98
2	1.0	4.0	5620	126	3.7	4790[d]	111	3.2	4160	103	2.9	3050	100	2.4	2020	97
4	1.9	8.1	5240	118	7.8	5130[d]	119	6.6	4250	105	5.8	3060	100	4.8	2140	103
7	3.4	14.7	4590	103	13.4	4510[d]	104	11.8	3760	93	10.4	2720	89	8.5	2090	101
10	4.8	21.5	4180	94	19.8	3870[d]	90	17.3	3440	85	15.1	2680	88	12.4	2170	104
3-YEAR TESTS																
0	0	0	5170	100	0	5020[c]	100	0	4480	100	0	3460	100	0	2400	100
1	0.5	2.0	5270	102	1.8	4680[d]	93	1.6	4370	97	1.4	3070	89	1.2	2330	97
2	1.0	4.0	5860	113	3.7	5540[d]	110	3.2	4600	103	2.9	3510	102	2.4	2310	96
4	1.9	8.1	5980	116	7.8	5840[d]	116	6.6	4990	111	5.8	3410	99	4.8	2310	96
7	3.4	14.7	5830	113	13.4	5040[d]	100	11.8	4450	99	10.4	3300	95	8.5	2190	91
10	4.8	21.5	4890	95	19.8	4590[d]	91	17.3	3850	86	15.1	3020	87	12.4	2180	91

[a] Per cent of weight of cement.
[b] Per cent of weight of mixing water based on the commercial product.
[c] Average of 25 tests.
[d] Average of 10 tests.
[e] Average of 4 tests.

TABLE V.—EFFECT OF CALCIUM CHLORIDE ON THE STRENGTH OF CONCRETE AS INFLUENCED BY DIFFERENT CURING CONDITIONS—SERIES 156.

Compression tests of 6 by 12-in. concrete cylinders.
Mix 1:5.2 by volume (1:2:4).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Cement: portland cement "A" purchased in Chicago.
Relative consistency 1.00 (Flow about 180, see Table XII).
Each value is the average of 9 tests made on different days, unless otherwise noted.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.
Calcium chloride and chlorine expressed as per cent of weight of cement.
Data plotted in Figs. 7 and 8. Compare Table VI.

Calcium Chloride *B*, per cent	Chlorine, per cent	Moist-Room Curing[a]		Water Curing		Air Curing	
		Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
28-DAY TESTS							
0	0	3310[b]	100	3140	100	2600	100
1	0.5	3240[c]	98	3160	101	2820	108
2	1.0	3430[c]	104	3440	110	3120	120
4	1.9	3620[c]	109	3210	102	3170	122
7	3.4	2890[c]	87	2620	83	2910	112
10	4.8	2460[c]	74	2630	84	2860	110
Average		3160	95	3030	97	2910	112
3-MONTH TESTS							
0	0	4170[b]	100	4080	100	2950	100
1	0.5	4060[c]	97	4100	101	3260	111
2	1.0	4470[c]	107	4330	106	3560	121
4	1.9	4550[c]	109	4260	104	3370	114
7	3.4	3780[c]	91	3770	92	3190	108
10	4.8	3320[c]	80	3590	88	3230	110
Average		4060	97	4020	99	3260	111
1-YEAR TESTS							
0	0	4320[b]	100	4520	100	2660	100
1	0.5	4480[c]	104	4520	100	3090	116
2	1.0	4790[c]	111	4890	108	3270	123
4	1.9	5130[c]	119	4690	104	3240	122
7	3.4	4510[c]	104	4330	96	2760	104
10	4.8	3870[c]	90	4350	96	2840	107
Average		4520	105	4550	101	2980	112
3-YEAR TESTS							
0	0	5020[b]	100	4720	100	2990	100
1	0.5	4680[c]	93	4990	106	3280	110
2	1.0	5540[c]	110	5080	108	3680	123
4	1.9	5840[c]	116	5180	110	3390	113
7	3.4	5040[c]	100	5240	111	3240	108
10	4.8	4590[c]	91	4700	100	3020	101
Average		5120	102	4970	106	3270	109

[a] Same values used in Table I.
[b] Average of 25 tests.
[c] Average of 10 tests.

TABLE VI.—EFFECT OF CALCIUM CHLORIDE ON THE STRENGTH OF CONCRETE AS INFLUENCED BY DIFFERENT CURING CONDITIONS—SERIES 158.

Compression tests of 6 by 12-in. concrete cylinders.
Mix 1:5.2 by volume (1:2:4).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Cement: a mixture of four brands of portland cement purchased in Chicago (Laboratory cement).
Relative consistency 1.00 (Flow about 180, see Table XII).
Each value is the average of 5 tests made on different days.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.
Calcium chloride expressed in terms of weight of cement.
Data plotted in Figs. 9 and 10.

Calcium Chloride *B*, per cent	Cured in Moist Room for Periods Indicated; Remainder in Air															
	0		3 Days		7 Days		14 Days		28 Days		3 Months		6 Months		1 Year	
	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
7-DAY TESTS																
0	1340	100	1450	100	1310	100	....	...	....	...	....	...	....	...	....	...
1	1580	118	1600	110	1530	117	....	...	....	...	....	...	....	...	....	...
2	1660	124	1830	126	1610	123	....	...	....	...	....	...	....	...	....	...
4	1800	134	1830	126	1530	117	....	...	....	...	....	...	....	...	....	...
7	1580	118	1680	116	1270	97	....	...	....	...	....	...	....	...	....	...
10	1550	116	1580	109	1180	90	....	...	....	...	....	...	....	...	....	...
Average	1590	119	1660	114	1400	107	....	...	....	...	....	...	....	...	....	...
28-DAY TESTS																
0	2080	100	2220	100	2720	100	2650	100	2640	100	....	...	....	...	....	...
1	2270	109	2450	110	2860	105	2830	107	2610	99	....	...	....	...	....	...
2	2290	110	2640	119	2980	110	3200	121	2810	106	....	...	....	...	....	...
4	2470	119	2710	122	3040	112	3100	117	2560	97	....	...	....	...	....	...
7	2330	112	2530	114	2870	105	3000	113	2250	85	....	...	....	...	....	...
10	2360	113	2480	112	2750	101	2770	104	2030	77	....	...	....	...	....	...
Average	2300	111	2600	113	2870	105	2920	110	2490	94	....	...	....	...	....	...
3-MONTH TESTS																
0	2530	100	2630	100	3110	100	3500	100	4120	100	3380	100	....	...	....	...
1	2580	102	2660	101	3450	111	3670	105	4020	97	3560	105	....	...	....	...
2	2750	108	3170	121	3610	116	3670	105	4100	100	3640	108	....	...	....	...
4	2880	114	2880	110	3260	105	3890	111	4150	101	3480	103	....	...	....	...
7	2510	99	2710	103	2880	93	3380	97	3750	91	3380	100	....	...	....	...
10	2640	104	2580	98	3030	98	3310	95	3710	90	2940	87	....	...	....	...
Average	2650	105	2770	105	3220	104	3570	102	3980	97	3400	101	....	...	....	...
6-MONTH TESTS																
0	2490	100	2560	100	3060	100	3660	100	3860	100	4520	100	4110	100	....	...
1	2570	103	2880	113	3230	106	3690	101	3960	103	4520	100	3920	95	....	...
2	2750	110	3130	125	3630	115	3900	107	4330	112	4690	104	4240	103	....	...
4	2720	109	3110	123	3350	109	3810	104	4280	111	4760	105	4050	98	....	...
7	2520	101	2760	109	2750	90	3300	90	3580	93	4240	94	3850	94	....	...
10	2110	85	2410	95	2590	88	2850	78	3450	89	4050	90	3380	82	....	...
Average	2530	110	2800	101	3080	101	3530	97	3910	101	4460	99	3930	95	....	..
1-YEAR TESTS																
0	3420	100	2790	100	3110	100	3140	100	4050	100	4370	100	4990	100	4790	100
1	2540	74	2800	100	3040	98	3650	116	3910	96	4440	102	5060	101	4590	96
2	2610	76	2980	107	3230	104	3880	123	4340	107	4370	100	4910	99	4520	94
4	2410	70	3400	122	3440	111	3930	125	4030	100	4510	103	5160	103	4080	85
7	2830	83	2800	100	3100	100	3370	107	3650	90	4000	91	4910	99	4320	90
10	2420	71	2460	88	2810	90	3460	110	3770	93	4200	96	4260	85	3800	79
Average	2700	79	2870	103	3120	101	3570	114	3960	99	4320	98	4880	98	4350	91
2½-YEAR TESTS																
0	2540	100	2560	100	3180	100	3360	100	3900	100	4190	100	5270	100	4980	100
1	2760	109	2790	109	3500	110	3550	106	3850	99	4150	99	4730	90	4840	97
2	2860	113	3350	131	3550	112	3680	110	3800	97	4360	104	5110	97	5620	113
4	3050	120	3140	123	3460	109	3460	103	3980	102	4420	106	4940	94	5730	115
7	2780	109	2850	111	2980	94	3160	94	3540	91	3870	92	4380	83	4880	98
10	2610	103	2760	108	3030	95	2970	88	3420	88	3560	85	4170	79	4340	87
Average	2770	109	2910	114	3280	103	3360	100	3750	96	4090	98	4770	91	5060	102

TABLE VII.—EFFECT OF CALCIUM CHLORIDE ON THE STRENGTH OF CONCRETE AND MORTAR AS INFLUENCED BY BRAND OF CEMENT—SERIES 156.

Compression tests of 6 by 12-in. concrete cylinders and 2 by 4-in. mortar cylinders.
Mix 1:5.2 by volume for concrete; 1:2.5 by volume for mortar.
Aggregate: sand and pebbles from Elgin, Ill.; sand graded 0 to No. 4 and sand and pebbles graded 0 to 1½ in.
Cement: 4 brands of portland cement "A," "B," "C" and "D" purchased in Chicago.
Relative consistency 1.00 (Flow about 180 for concrete and 130 for mortar, see Table XII).
Concrete specimens cured in moist room and mortar specimens in water until test; tested damp.
Each value for concrete strength is the average of 9 tests made on different days and for mortar 5 tests unless otherwise noted.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.
Calcium chloride and chlorine expressed in terms of weight of cement.
Data plotted in Fig. 11. Compare Table VIII.

Age at Test	Calcium Chloride *B*, per cent	Chlorine, per cent	Cement A		Cement B		Cement C		Cement D		Average Strength-Ratio per cent
			Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	
COMPRESSION TESTS OF 6 BY 12-IN. CONCRETE CYLINDERS											
2 days.......	0	0	950[a]	100	750	100	570	100	740	100	100
"	4	1.9	1400[b]	147	810	108	810	142	1130	153	138
7 days.......	0	0	1940[a]	100	1640	100	1240	100	1620	100	100
"	4	1.9	2220[b]	114	1620	99	1530	123	2130	131	117
28 days......	0	0	3310[a]	100	2990	100	2150	100	2650	100	100
"	4	1.9	3620[b]	109	2870	96	2520	117	3170	119	110
3 months....	0	0	4170[a]	100	4220	100	3030	100	3860	100	100
"	4	1.9	4550[b]	109	4230	100	3450	114	4000	104	107
1 year.......	0	0	4320[a]	100	4580	100	3410	100	3890	100	100
"	4	1.9	5130[b]	119	4960	108	3870	113	4490	115	114
3 years......	0	0	5020[a]	100	5480	100	4100	100	4840	100	100
"	4	1.9	5840[b]	116	5830	106	4430	108	4880	101	108
COMPRESSION TESTS OF 2 BY 4-IN. MORTAR CYLINDERS											
2 days.......	0	0	1970[c]	100	1840	100	1550	100	1450	100	100
"	4	1.9	2290	116	1490	81	1850	119	2330	161	119
7 days.......	0	0	3610[c]	100	3190	100	3190	100	3270	100	100
"	4	1.9	3640	101	2680	84	3420	107	4240	130	106
28 days......	0	0	5100[c]	100	4710	100	4670	100	4740	100	100
"	4	1.9	4570	90	4760	101	4550	98	5900	125	103
3 months....	0	0	6080[c]	100	5440	100	5500	100	5980	100	100
"	4	1.9	5180	85	6230	114	6290	114	6310	105	104
1 year.......	0	0	6520[c]	100	6060	100	6710	100	6520	100	100
"	4	1.9	5300	81	7280	120	7320	109	8070	124	108
3 years......	0	0	6820[c]	100	7030	100	6920	100	7100	100	100
"	4	1.9	5590	82	7550	107	7200	104	7990	112	101

[a] Average of 25 tests.
[b] Average of 10 tests.
[c] Average of 15 tests.

Table VIII.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Brand of Cement—Series 158.

Compression tests of 6 by 12-in. concrete cylinders.
Mix 1:5.2 by volume (1:2:4).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Cement: 4 brands of portland cement "A," "B," "C" and "D" purchased in Chicago.
Relative consistency 1.00 (Flow about 180, see Table XII).
Specimens cured in moist room for 14 days; remainder in air.
Each value is the average of 5 tests made on different days.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.
Calcium chloride expressed in terms of weight of cement.
Compare Table VII.

Calcium Chloride *B*, per cent	Laboratory Cement[a]		Cement A		Cement B		Cement C		Cement D	
	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength lb. per sq. in.	Strength-Ratio, per cent
28-day Tests										
0	2650	100	2830	100	2500	100	2470	100	2170	100
1	2830	107	2660	94	2840	114	2610	106	2290	105
2	3200	121	2770	98	2600	104	2850	115	2460	113
4	3100	117	2630	93	2620	105	2950	119	2720	125
7	3000	113	3030	107	3140	126	2690	109	2660	123
10	2770	104	2810	99	2940	118	2770	112	2720	125
Average	2920	110	2790	99	2770	111	2720	110	2500	115
3-month Tests										
0	3500	100	3610	100	3290	100	3330	100	3070	100
1	3670	105	3250	90	3550	108	3110	93	2910	95
2	3670	105	3490	97	3680	112	3610	108	2880	94
4	3890	111	3340	92	3930	119	3820	114	3220	105
7	3380	97	3560	99	3390	103	3180	96	3190	104
10	3310	95	3630	101	3200	97	3220	97	2900	94
Average	3570	102	3480	96	3510	106	3380	101	3030	99
6-month Tests										
0	3660	100	3430	100	3100	100	3340	100	2840	100
1	3690	101	3590	105	3520	114	3390	102	2890	104
2	3900	107	3520	103	3550	115	3920	117	3060	108
4	3810	104	3450	101	3660	118	3590	107	2730	96
7	3300	90	3610	105	3470	112	3170	95	2650	93
10	2850	78	3380	99	2930	95	2810	84	3040	107
Average	3530	97	3500	102	3370	109	3370	101	2870	101
1-year Tests										
0	3140	100	3660	100	3340	100	3500	100	2870	100
1	3650	116	3420	93	3630	109	3530	101	2900	101
2	3880	124	3570	98	3790	114	3640	104	3040	106
4	3930	125	3430	94	3630	109	3590	103	3090	108
7	3370	107	3940	108	3440	103	3290	94	2820	98
10	3460	110	3300	90	3270	98	2980	85	2700	94
Average	3570	114	3550	97	3520	106	3420	98	2900	101
2½-year Tests										
0	3360	100	3430	100	3370	100	3390	100	2860	100
1	3550	106	3770	110	3320	99	3660	108	2850	100
2	3680	110	3770	110	3600	107	3630	107	3040	106
4	3460	103	3310	96	3560	106	3580	106	3080	108
7	3160	94	3450	101	3150	93	3120	92	3470	121
10	2970	88	3380	99	3100	92	2930	86	2700	94
Average	3360	100	3520	103	3350	100	3380	100	3000	105

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[a] A mixture of the four brands, A, B, C and D, given above, but not of the same lot; same cement used for tests in Table VI. The individual brands are the same as those in Series 156, but not the same lots.

TABLE IX.—EARLY STRENGTH OF CONCRETE CURED AT LOW TEMPERATURES—SERIES 188

Compression tests of 6 by 12-in. cylinders.
Mix: 1:5 by volume.
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1¼ in. (fineness modulus, 5.65).
Cement: a mixture of four brands purchased in Chicago.
Relative consistency 1.25. (Slump about 8 in. Flow test not made.)
Outdoor temperatures ranged from 24 to 37° F. The aggregate, cement and water were stored outdoors in covered metal cans 18 to 20 hours before use.
Specimens cured outdoors were kept under wet burlap for 14 days; remainder in air; laboratory cured cylinders were placed in moist room on the day molded
Calcium chloride expressed in terms of weight of cement.
Strength-ratios are percentages of the strength of concrete specimens made and cured in laboratory under standard conditions.
Each value is the average of 6 tests made on different days.
Data plotted in Fig. 16

Place Made	Place Cured	Temperature, deg. Fahr.		Calcium Chloride, per cent	Temperature of Concrete after Molding, deg. Fahr								1 day		2 days		4 days		7 days		14 days		28 days		3 months	
		Cement and Aggregate	Mixing Water		0 min.	15 min.	30 min.	1 hr.	2 hr.	3 hr.	4 hr.	20 hr.	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
Laboratory	Laboratory	66	63	0	64	66	64	64	64	63	64	64	150	100	410	100	830	100	1230	100	1880	100	2640	100	4620	100
Laboratory	Outdoors	66	63	0	64	66	64	64	63	59	57	36	65	43	100	24	160	19	430	35	1020	54	1670	63	2930	63
Laboratory	Laboratory	66	66	3	66	68	68	66	64	61	61	66	260	173	600	146	950	114	1260	102	1790	95	2320	88	3670	79
Laboratory	Outdoors	66	66	3	66	66	66	66	64	61	61	36	75	50	200	49	460	55	750	61	1130	60	1820	69	2670	58
Outdoors	Outdoors	37	36	0	37	37	39	37	37	37	39	36	15	10	45	11	120	14	300	24	850	45	1660	63	2820	61
Outdoors	Laboratory	37	36	0	37	37	37	37	36	36	37	64	45	30	180	44	560	67	960	78	1570	84	2680	101	4410	95
Outdoors	Outdoors	37	39	3	39	39	39	39	39	41	41	36	50	33	185	45	415	50	710	58	1120	60	1980	75	2900	63
Outdoors	Laboratory	37	39	3	39	39	39	39	37	37	39	64	160	107	380	93	670	81	1010	82	1640	87	2160	82	3440	74
Outdoors	Outdoors	37	66	0	45	43	43	41	39	41	39	36	15	10	60	15	160	19	420	34	950	50	1690	64	2740	59
Outdoors	Outdoors	37	124	0	59	52	50	46	61	59	37	34	15	10	65	16	180	22	470	38	1060	56	1850	70	2890	63
Outdoors	Outdoors	37	199	0	73	64	61	54	46	63	61	34	15	10	80	20	220	27	490	40	1200	64	1930	73	3120	68
Outdoors	Outdoors	59	36	0	54	50	48	45	41	39	39	33	15	10	60	15	140	17	385	31	1070	57	2030	77	2960	64
Outdoors	Outdoors	57	66	0	59	55	54	66	63	63	41	34	20	13	55	13	150	18	410	33	1180	63	2040	77	3400	74
Outdoors	Outdoors	61	124	0	70	64	59	55	52	46	45	36	20	13	80	20	185	22	465	38	1230	65	1920	73	2970	64
Outdoors	Outdoors	63	203	0	88	77	75	64	57	50	48	36	20	13	80	20	200	24	520	42	1150	61	1890	72	2880	62

TABLE X.—MAXIMUM STRENGTH-RATIOS FOR CONCRETE AND MORTAR USING CHEMICAL ADMIXTURES—SERIES 156.

Based on data in Tables I and II and Fig. 1.
Mix for concrete, 1:5.2; for mortar, 1:2.5 by volume.
Relative consistency 1.00.

Chemical Admixture	Calcium Chloride Content, per cent by Weight	Maximum Strength-Ratio[a]						Percentage of Admixture at which Maximum Strength Occurs					
		2 days	7 days	28 days	3 months	1 year	3 years	2 days	7 days	28 days	3 months	1 year	3 years
6 BY 12-IN. CONCRETE CYLINDERS													
None	0	950[c]	1940[c]	3310[c]	4170[c]	4320[c]	5020[c]	...	...	...	...	...	...
Calcium Chloride, *A*	74	170	125	110	112	117	118	4 1.9[b]	3 1.5	3 1.5	3 1.5	4 1.9	4 1.9
Calcium Chloride, *B*	75	147	124	109	109	119	116	4 1.9[b]	2 1.0	4 1.9	4 1.9	4 1.9	4 1.9
Cal (standard chlorine)	25	151	123	107	107	121	119	7 1.1[b]	7 1.1	7 1.1	10 1.6	10 1.6	7 1.1
Cal (low chlorine)	17	143	118	101	104	113	111	10 1.1[b]	10 1.1	7 0.7	10 1.1	10 1.1	15 1.6
Vitriflux	34	138	115	106	108	109	114	7 1.5[b]	7 1.5	6 1.3	7 1.5	4 0.9	7 1.5
Magnesium chloride	46 ($MgCl_2$)	115	Decrease for all percentages					1 0.3[b]	0 0	0 0	0 0	0 0	0 0
2 BY 4-IN. MORTAR CYLINDERS (0 TO NO. 4 ELGIN SAND)													
None	0	1970[d]	3610[d]	5100[d]	6080[d]	6520[d]	6820[d]	...	...	...	...	...	...
Calcium chloride, *A*	74	146	120	109	107	106	106	2 1.0[b]	2 1.0	2 1.0	2 1.0	2 1.0	1 0.5
Calcium chloride, *B*	75	130	110	Decrease for all percentages				2 1.0[b]	2 1.0	0 0	0 0	0 0	0 0
Cal (standard chlorine)	25	162	136	122	122	121	130	7 1.1[b]	7 1.1	7 1.1	7 1.1	7 1.1	7 1.1
Cal (low chlorine)	17	139	124	107	107	107	100	10 1.1[b]	10 1.1	7 0.7	7 0.7	10 1.1	10 1.1
Vitriflux	34	148	128	114	108	108	103	4 0.9[b]	4 0.9	4 0.9	4 0.9	4 0.9	1 0.2
Magnesium chloride	46 ($MgCl_2$)	131	112	106	110	110	110	2 0.7[b]	2 0.7	4 1.4	2 0.7	2 0.7	1 0.3

[a] Percentage of strength of similar concrete or mortar at given age without admixture.
[b] Percentage of chlorine based on weight of cement.
[c] Strength of concrete without admixture, lb. per sq. in.
[d] Strength of mortar without admixture, lb. per sq. in.

TABLE XI.—SUMMARY OF TESTS ON CALCIUM CHLORIDE IN CONCRETE.

Item	Compressive Strength Without Admixture, lb. per sq. in.						Maximum Strength-Ratio Using Calcium Chloride						Per cent Calcium Chloride Giving Maximum Strength					
	2 days	7 days	28 days	3 mo.	1 year	3 years	2 days	7 days	28 days	3 mo.	1 year	3 years	2 days	7 days	28 days	3 mo.	1 year	3 years
EFFECT OF MIX—SERIES 156—RELATIVE CONSISTENCY 1.00; CEMENT A; SEE TABLE III AND FIG. 3																		
Mix 1:7	540	1100	2060	2790	3050	3500	120	106	[a]	[a]	[a]	[a]	4	2	0	0	0	0
Mix 1:5.2	950	1940	3310	4170	4320	5020	147	124	109	109	119	116	4	2	4	4	4	4
Mix 1:4	1350	2660	4240	5140	5750	6390	149	130	116	112	110	113	2	2	2	2	2	2
Mix 1:3	1960	3680	4920	5960	6490	7530	159	130	128	118	113	116	2	2	4	2	4	2
Mix 1:2	2780	4530	5750	6140	7090	8390	149	130	123	131	107	107	2	2	2	4	4	2
EFFECT OF CONSISTENCY—SERIES 156—MIX 1:5.2; CEMENT A; SEE TABLE IV AND FIG. 5																		
Rel. Consist. 0.90	1110	2370	3830	4590	4450	5170	153	116	100	104	126	116	2	2	4	4	2	4
" " 1.00	950	1940	3310	4170	4320	5020	147	124	109	109	119	116	4	2	4	4	4	4
" " 1.10	720	1560	2750	3830	4030	4480	144	115	101	101	105	111	2	2	4	2	4	4
" " 1.25	440	1070	2100	2840	3060	3460	159	117	[a]	[a]	[a]	102	2	2	0	0	0	2
" " 1.50	280	640	1200	1860	2080	2400	146	122	107	[a]	104	[a]	2	2	2	0	10	0
EFFECT OF CURING CONDITION—SERIES 156—MIX 1:5.2; RELATIVE CONSISTENCY 1.00; CEMENT A; SEE TABLE V AND FIGS. 7 AND 8																		
Moist Room	....	....	3310	4170	4320	5020	...	...	109	109	119	116	..	..	4	4	4	4
Water Curing	....	....	3140	4080	4520	4720	...	...	110	106	108	111	..	..	2	2	2	7
Air Curing	....	....	2600	2950	2660	2990	...	...	122	121	123	123	..	..	4	2	2	2
EFFECT OF CURING CONDITION—SERIES 158—MIX 1:5.2; RELATIVE CONSISTENCY 1.00; CEMENT, 4 BRANDS; SEE TABLE VI AND FIGS. 9 AND 10																		
Moist Room, 0 days[c]	....	1340	2080	2530	3420	2540	...	134	119	114	[a]	120	..	4	4	4	0	4
" " 3 days[c]	....	1450	2220	2630	2790	2560	...	126	122	121	122	131	..	2	4	2	4	2
" " 7 days[c]	....	1310	2720	3110	3110	3180	...	123	112	116	111	112	..	2	4	2	4	2
" " 14 days[c]	....	....	2660	3500	3140	3360	...	...	121	111	125	110	..	..	2	4	4	2
" " 28 days[c]	....	....	2640	4120	4050	3900	...	...	106	101	107	102	..	..	2	4	2	4
" " 3 mo.[c]	....	....	....	3380	4370	4190	...	...	...	108	103	106	..	..	..	2	4	4
" " 6 mo.[c]	....	....	....	....	4990	5270	...	...	...	...	103	[a]	..	..	..	..	4	0
" " 1 year[c]	....	....	....	....	4790	4980	...	...	...	..	[a]	115	..	..	..	..	0	4
EFFECT OF BRAND OF CEMENT—SERIES 156—MIX 1:5.2; RELATIVE CONSISTENCY 1.00; SEE TABLE VII AND FIG. 11																		
Cement A	950	1940	3310	4170	4320	5020	147	114	109	109	119	116	Tests made for 4 per cent calcium chloride only					
" B	750	1640	2990	4220	4580	5480	108	[a]	[a]	[a]	108	106						
" C	570	1240	2150	3030	3410	4100	142	123	117	114	113	108						
" D	740	1620	2650	3860	3890	4840	153	131	119	104	115	101						
EFFECT OF BRAND OF CEMENT[b]—SERIES 158—MIX 1:5.2; RELATIVE CONSISTENCY 1.00; SEE TABLE VIII																		
Cement, Lab.	....	....	2650	3500	3140	3360	...	...	121	111	125	110	..	..	2	4	4	2
" A	....	....	2830	3610	3660	3430	...	...	107	101	108	110	..	..	7	10	7	1
" B	....	....	2500	3290	3340	3370	...	...	126	119	114	107	..	..	7	4	2	2
" C	....	....	2470	3330	3500	3390	...	...	119	114	104	108	..	..	4	4	2	1
" D	....	....	2170	3070	2870	2860	...	...	125	105	108	121	..	..	4	4	4	1

[a] Decrease in strength with all percentages of calcium chloride.
[b] Cured 14 days in moist room; remainder in dry air.
[c] Remainder in air of laboratory.

TABLE XII.—WATER-RATIOS AND FLOW TESTS—SERIES 156.

Water is expressed as the ratio of volume of water to volume of cement.

Plasticity of the concrete and mortar was measured by means of the flow table. The apparatus consists of a truncated cone and a table mounted on a cam in such a way that it can be raised and dropped ½ inch. For concrete, a truncated cone 6¾ by 10 by 5 in. was used with a table 25½ in. in diameter. For the mortar tests the truncated cone was 4 by 6 by 3 in. and the table 17 in. in diameter. The concrete or mortar to be tested was molded in the cone on the table. Immediately after filling, the cone was withdrawn and the table dropped 15 times in about 10 seconds. The base diameter of the concrete was measured and this diameter expressed as a percentage of the base diameter of the cone is the "flow".

Five to ten specimens were made in each set on different days. The flow was determined only for the first specimen in a set. The same quantity of mixing water was used throughout the set.

Admixture expressed as per cent of weight of cement.

A. CONCRETE AND MORTAR TESTS; TABLES I AND II

Admixture, per cent	Calcium Chloride *A*		Calcium Chloride *B*		Cal				Vitriflux		Magnesium Chloride	
					Standard		Low Chlorine					
	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow
1:5.2 CONCRETE; SEE TABLE I												
0[c]	0.85	173	0.85	173	0.85	173	0.85	173	0.85	173	0.85	173
1	0.85	180[a]	0.85	172	....	...	....	...	0.85	177	0.89	185
2	0.83	180[a]	0.84	169	0.86	180	0.86	172	0.85	181	0.91	185
4	0.80	176[a]	0.80	160	0.86	187	0.86	176	0.85	177	0.93	190
7	0.84	177[a]	0.84	169	0.86	179	0.86	176	0.85	185	0.91	181
10	0.83	163[a,b]	0.84	160[e]	0.86	176	0.88	171	0.85	186	0.94	178
15	....	...	....	...	0.88	185	0.88	171	0.85	181	....	...
20	....	...	....	...	0.90	190	0.90	172	....	...	....	...
1:2½ MORTAR; SEE TABLE II												
0[d]	0.58	125	0.58	125	0.58	125	0.58	125	0.58	125	0.58	125
1	0.58	123	0.56	118	....	...	....	...	0.57	122	0.64	135
2	0.62	119	0.58	116	0.60	131	0.60	133	0.59	126	0.70	144
4	0.69	126	0.58	122	0.61	138	0.61	132	0.61	128	0.78	141
7	....	...	....	...	0.61	140	0.61	132	0.63	123	0.93	143
10	....	...	....	...	0.62	146	0.62	143	0.65	120	....	...
15	....	...	....	...	0.62	146	0.62	136	....	...	....	...
20	....	...	....	...	0.63	152	0.63	133	....	...	....	...

[a] Average of 8 tests.

[b] Values for flow erratic due to quick stiffening. Omitting three sets of low values, the average becomes 179.

[c] Average of 25 tests.

[d] Average of 15 tests.

[e] Values of flow erratic due to quick stiffening.

TABLE XII—*Continued.*

B. CONCRETE TESTS; SEE TABLE III

Calcium Chloride B, per cent	Mix by Volume									
	1:7		1:5		1:4		1:3		1:2	
	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow
0	1.09	166	0.85	173	0.73	174	0.58	172	0.49	170
1	1.11	180	0.85	172	0.73	175	0.60	168	0.49	166
2	1.14	179	0.84	169	0.71	177	0.58	137	0.48	168
4	1.10	178	0.80	160	0.70	185	0.58	171	0.49	180
7	1.10	169	0.84	169	0.69	166	0.58	161	0.54	211
10	1.08	174	0.84	160	0.74	189	0.58	163	0.54	195

C. 1:5.2 CONCRETE; SEE TABLE IV

Calcium Chloride B, per cent	Relative Consistency									
	0.90		1.00		1.10		1.25		1 50	
	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow[f]	Water-Ratio	Flow[f]
0	0.76	152	0.85	173	0.94	200	1.06	...	1.28	...
1	0.76	154	0.85	172	0.94	202	1.07	...	1.29	...
2	0.76	150	0.84	169	0.94	210	1.06	...	1.28	...
4	0.76	151	0.80	160	0.94	205	1.07	...	1.28	...
7	0.76	160	0.84	169	0.94	196	1.07	...	1.28	...
10	0.76	157	0.84	160	0.94	208	1.06	...	1.28	...

D. 1:5.2 CONCRETE; SEE TABLE V

Calcium Chloride B, per cent	Moist Room Curing		Water Curing		Air Curing	
	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow
0	0.85	173	0.85	175	0.85	180
1	0.85	172	0.85	174	0.85	180
2	0.84	169	0.85	180	0.85	184
4	0.80	160	0.85	179	0.85	184
7	0.84	169	0.85	184	0.85	183
10	0.84	160	0.83	177	0.83	170

E. CONCRETE AND MORTAR TESTS WITH DIFFERENT CEMENTS; TABLE VII

Calcium Chloride B, per cent	Cement A		Cement B		Cement C		Cement D	
	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow
1:5.2 CONCRETE; SEE TABLE VII								
0	0.85	173	0.85	164	0.85	157	0.85	163
4	0.80	160	0.85	163	0.85	155	0.85	167
1:2½ MORTAR; SEE TABLE VII								
0	0.58	125	0.59	133	0.63	139	0.62	132
4	0.58	122	0.82	161	0.77	137	0.75	139

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[f] Over limit of flow table.

TABLE XIII.—TESTS OF CEMENTS.

MISCELLANEOUS TESTS

Tests made in accordance with the Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.

Each value is the average of 2 to 4 tests.

Series	Cement	Residue on No. 200 Sieve	Water for Normal Consistency, per cent by Weight	Time of Setting								Soundness Test (over boiling water)
				Vicat Needle				Gillmore Needle				
				Initial		Final		Initial		Final		
				hr.	min.	hr.	min.	hr.	min.	hr.	min.	
156	A	17.6	23.0	1	30	3	35	2	15	5	30	O.K.
	B	19.8	24.5	2	45	5	00	3	50	6	20	O.K.
	C	21.0	24.0	2	50	6	05	4	10	7	05	O.K.
	D	11.6	24.0	2	40	5	25	4	10	6	55	O.K.
158	Laboratory	17.4	23.5	3	40	7	50	6	20	8	55	O.K.
188	Laboratory	18.4	23.5	3	40	6	50	5	25	7	55	O.K.

STRENGTH TESTS

1:3 standard sand mortar.

Tests made in accordance with the Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.

Specimens cured in water; tested damp.

Each value is the average of 5 to 10 tests made on different days.

Series	Cement	Mixing Water, per cent	Tensile Strength of Briquettes, lb. per sq. in.					Compressive Strength of 2 by 4-in. Cylinders, lb. per sq. in.				
			3 days	7 days	28 days	3 months	1 year	3 days	7 days	28 days	3 months	1 year
156	A	10.3	220	250	360	375	400	960	1750	2890	3520	3650
	B	10.6	175	235	365	430	405	1020	1630	2930	3750	3280
	C	10.5	180	245	340	420	390	830	1450	2170	2850	3030
	D	10.5	185	265	375	415	385	1140	1710	3030	3690	3180
158	Laboratory	10.5	...	270	390	430	440	....	1660	2520	3340	3890
188	Laboratory	10.4	...	310	405	450	....	....	1820	2930	3950	....

TABLE XIV.—INFLUENCE OF ADMIXTURES ON TIME OF SETTING OF CEMENT—SERIES 156.

Tests for time of setting made with Cement A, only.

Admixture	Calcium Chloride, per cent	Chlorine Combined as Chloride, per cent	Admixture, per cent of weight of cement	Normal Consistency, per cent by weight	Time of Setting								Soundness Test (over boiling water)
					Vicat Needle				Gillmore Needle				
					Initial		Final		Initial		Final		
					hr.	min.	hr.	min.	hr.	min.	hr.	min.	
None	..	....	0	23.0	1	30	3	35	2	15	5	30	O.K.
Calcium chloride, *A*	74	47.5	1	22.0	1	20	3	05	2	10	3	15	O.K.
			2	23.0	1	20	2	25	2	00	3	10	O.K.
			4[a]	25.0	0	10	1	10	0	20	1	20	O.K.
Calcium chloride, *B*	75	48.0	1	22.0	1	10	2	30	2	00	3	05	O.K.
			2	23.0	1	00	2	10	1	30	2	40	O.K.
			4[a]	25.0	0	10	0	40	0	20	1	10	O.K.
Cal (low chlorine)	17	10.6	2	23.0	1	20	3	00	2	10	4	50	O.K.
			4	23.5	1	10	2	55	2	20	3	30	O.K.
			7	24.5	1	00	2	20	2	20	3	30	O.K.
			10	25.0	0	45	2	15	1	50	2	35	O.K.
			15	26.0	0	40	1	20	1	20	2	10	O.K.
			20	29.0	0	20	1	20	1	10	2	00	O.K.
Vitriflux	34	21.4	1	22.5	0	55	3	15	1	50	3	40	O.K.
			2	22.5	1	05	2	30	2	00	3	30	O.K.
			4	22.5	0	50	2	00	1	45	2	40	O.K.
			7	23.0	0	05	1	30	0	10	1	20	O.K.
			10	24.5	Flash Set								O.K.
Magnesium chloride	46[b]	34.4	1	22.5	1	20	3	10	2	35	3	50	O.K.
			2	23.0	1	20	6	10	2	30	3	50	O.K.
			4	24.5	1	10	2	40	2	05	3	15	O.K.
			7[a]	27.0	0	40	1	50	1	40	3	00	O.K.

[a] Higher percentages gave flash set.
[b] Magnesium chloride.

TABLE XV.—CHEMICAL ANALYSES OF CEMENTS.

Tests made in accordance with Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.
Values are the average of 2 tests expressed as percentages by weight.

Cement	Silica (SiO_2)	Iron and Aluminum Oxides ($Fe_2O_3+Al_2O_3$)	Calcium Oxide (CaO)	Magnesium Oxide (MgO)	Sulfuric Anhydride (SO_3)	Loss on Ignition	Insoluble Residue
			SERIES 156				
A	20.89	9.58	62.95	2.24	1.58	2.06	0.34
B	22.32	10.27	61.57	1.88	1.91	1.33	0.15
C	21.32	9.54	62.16	0.66	1.76	2.96	0.26
D	22.58	6.74	61.71	3.65	1.21	2.72	0.44
			SERIES 158				
Laboratory	21.11	9.38	61.95	2.68	1.78	2.16	0.40
A	19.42	10.74	62.93	2.25	1.53	2.75	0.26
B	21.08	10.48	61.62	1.76	2.72	1.97	0.38
C	20.96	10.63	62.97	1.43	1.54	2.15	0.18
D	20.52	8.20	63.00	4.04	1.45	2.32	0.20
			SERIES 188				
Laboratory	22.42	9.17	62.10	2.71	1.82	1.15	0.18

BIBLIOGRAPHY

The brief notes given in the following Bibliography are intended to indicate the conclusions of the authors of the respective papers; they do not necessarily reflect the views of the writer of this report based on a study of the same and later, more complete data.

"Influence of Calcium Chloride on Portland Cement," by E. Candlot, *Jahresbericht*, p. 850, 1889. Abstract, *Journal*, Soc. Chemical Ind., Vol. 8, p. 543, 1889. Ciments et Chaux Hydrauliques, p. 243, 1891.

Set was retarded.

"Hydration Processes," by P. Rohland, Bericht d. Deutsch. Chem. Ges., Vol. 33, p. 2831, 1901.

Set was accelerated; no details given.

"Influence of Chloride of Lime on Setting of Portland Cement," by F. Hauenschild, *Tonindustrie Zeitung*, Vol. 25, p. 1771, 1901. Abstract, *Journal*, Soc. Chemical Ind., Vol. 21, p. 175, 1902.

Bleaching powder or calcium oxychloride increases strength of cement curing in air, but useless for exposure to moisture.

"Abnormalities in Initial Setting of Cement," by N. Ljamin, *Tonindustrie Zeitung*, Vol. 26, p. 874, 1902. *Journal*, Soc. Chemical Ind., Vol. 21, p. 972, 1902.

Small amounts retard set; large amounts accelerate.

"Notes on Retardation of Setting of Portland Cement," by Nihoul and Dufossez, *Bulletin No. 3*, Scient. de l'Assoc. des Élèves des Écoles Speciales de Liege No. 3. Abstract, *Journal*, Soc. Chemical Ind., Vol. 21, p. 859, 1902.

"Hydration of Portland Cement," by P. Rohland, *Zeitschrift für Angewandte Chemie*, Vol. 16, pp. 622, 1049, 1903. *Journal*, Soc. Chemical Ind., Vol. 21, pp. 972, 1244, 1903. *Zeitschrift Elect. Chem.*, Vol. 10, p. 893, 1904.

Cement gaged with calcium chloride above 10 per cent showed decreasing setting time.

"Materials which Retard Setting of Portland Cement," by R. C. Carpenter, *Engineering Record*, Vol. 50 p. 769, December 31, 1904. *Cement Age*, Vol. 2, p. 207, 1906. *Engineering News*, Vol. 53, p. 13, 1905. *Sibley Journal Engineering*, Vol. 19, p. 143, 1905.

Addition of 0.5 per cent calcium chloride produced greatest retardation; had no injurious effect on ultimate strength.

"Retarding of Gypsum and Calcium Chloride on Setting of Portland Cement," *Cement Age*, Vol. 2, p. 207, 1905.

"Action of Aqueous Solutions of Calcium and Magnesium Chloride on Portland Cement," by O. von Blaese, *Tonindustrie Zeitung*, Vol. 30, p. 1734, September 22, 1906. *Chem. Zeitung*, Vol. 30, p. 444, 1906. *Journal*, Soc. Chemical Ind., Vol. 26, p. 19, 1907.

Maximum retardation produced with 2 per cent solution of calcium chloride and 6 per cent magnesium chloride.

"Étude Experimentale du Ciment Armé," by R. Feret, Published by Gauthier-Villars, Paris, 1906, p. 651.

Gaging with dilute and concentrated calcium chloride on strength of concrete studied. Nature of gaging water had little effect on strength.

"Prevention of Freezing of Concrete by Calcium Chloride," by R. K. Meade, *Engineering Record*, April 20, 1907.

"Calcium Chloride in Cement," *Cement Age*, Vol. 5, p. 130, 1907.

"Influence of Electrolytes on Setting of Portland Cement," by P. Rohland, *Stahl und Eisen*, Vol. 28, p. 1815, 1908. *Journal*, Soc. Chemical Ind., Vol. 28, p. 23, 1909.

Small amount of calcium chloride retards; large amount accelerates.

"Influence of Gypsum and Chloride of Calcium on Setting Time of Portland Cement," by R. C. Carpenter, *Concrete and Const. Eng.*, 1908. Abstract, *Engineering Digest*, Vol. 3, p. 385, 1908. *Chemical Abstracts* Vol. 2, p. 1609, 1908.

"Influence of Calcium Sulfate and Calcium Chloride on Portland Cement," by Spiegelberg, *Proceedings*, German Portland Cement Mfrs., p. 286, 1909. *Tonindustrie Zeitung*, Vol. 33, p. 1289, 1909. *Journal*, Soc. Chemical Ind., Vol. 28, p. 1131, 1909. *Chemical Abstracts*, Vol. 3, p. 3004, 1909.

Effect varies with composition and general properties of the cement.

"Results of Tests on Influence of Calcium Chloride on Mortar," by H. S. Spackman, *Rev. Mat. de Const. et Trav. Pub.*, March, 1910.

"Effect of Calcium Chloride on Portland Cement," by H. Burchartz, *Mitteilungen* a. d. kgl. Versuchsanstalten zu Berlin, Vol. 28, p. 338, 1910. *Journal*, Soc. Chemical Ind., Vol. 29, p. 108, 1910.

Small addition retards set; large amount accelerates. Four samples which were mixed with 20 per cent of the salt failed in soundness.

"Use of $MgSO_4$ and Other Soluble Salts in Cement Mortar," by A. B. Pacini (Metamorphism of Portland Cement), *Annals*, New York Acad. Sci., Vol. 22, p. 199, 1912.

"Influence of Calcium Chloride and Hydrochloric Acid on Portland Cement Clinker," by N. Achsharamov, *Rigasche Ind. Zeitung.*, p. 52, 1912. *Chemical Abstracts*, Vol. 6, p. 2987, 1912.

Calcium chloride accelerates hardening and increases strength; recommended for sea water construction.

"Influence of Solutions of Lime Salts on Cement," by O. Kallauner, *Chem. Listy.*, Vol. 7, p. 89, 1913. *Chem. Zeitung*, Vol. 37, p. 448, 1913. *Chemical Abstracts*, Vol. 7, p. 3651, 1913.

Calcium chloride caused softening of cement after 28 days and corrosion after 90 days.

"Viscosity of Calcium Chloride Solutions," by F. Simeon, *Phil. Mag.*, Vol. 27, p. 95, 1913.

"Effect of Sodium Chloride and Calcium Chloride on Strength of Concrete," *Engineering Record*, Vol. 68, p. 466, 1913.

"Effect of Calcium Salts on Portland Cement," by O. Kallauner, *Proceedings*, German Portland Cement Mfrs., Vol. 3, p. 213, 1914. *Zeitschrift Betonbau*, No. 2, 1914. *Chemical Abstracts*, Vol. 8, p. 2236, 1914.

Decreases strength; concludes that all soluble calcium salts decompose cement.

"Calcium Chloride Hastens Setting of Concrete," by R. J. Wig, *Engineering Record*, Vol. 74, p. 266, 1916.

Shows the effect of various salt additions on strength of 1:3 mortar.

"Calcium Chloride to Accelerate Hardening," *Concrete*, Vol. 9, p. 28, July, 1916.

"Some Generalizations on Influence of Substances on Cement and Concrete," by J. C. Witt, *Philippine Journal Sci.*, Vol. 13, January, 1918.

"Effect of Calcium Chloride on Concrete," Annual Report, New York Commissioner of Highways, p. 61, 1918. Abstract, *Engineering News-Record*, Vol. 82, p. 1259, June 26, 1919. Abstract, *Good Roads*, July 9, 1919.

"Influence of Calcium Chloride on the Hardening of Concrete," *Rev. Mat. de Const. et Trav. Pub.*, p. 337, December, 1919.

"Effect of Calcium Chloride and Sodium Chloride on Strength of Concrete," by Pulver and Johnson, Johnson's "Materials of Construction," by Withey and Aston, p. 498, 1919.

Compression tests on 4-in. cubes at ages of 14, 60 and 360 days at room temperature and at freezing temperatures; calcium chloride increased strength.

"Effect of Calcium Chloride on Steel," *Engineering News-Record*, Vol. 84, p. 973, 1920.

"Tests Show More Strength, Less Absorption," *Concrete*, p. 162, March, 1920.

Tests using Vitriflux (solution of calcium chloride).

"'Cal' to Increase Rate of Hardening of Concrete," *Concrete* (CMS), p. 79, March, 1920.

"Cal" is an oxychloride of calcium. Tests made by U. S. Bureau of Standards.

"Further discussion of 'Cal' " by S. W. Stratton, *Concrete* (CMS), p. 55, October, 1920.

"Effects of 'Cal' as an Accelerator of the Hardening of Portland Cement," by R. N. Young, U. S. Bureau of Standards *Technologic Paper No. 174*, October 11, 1920. Abstract, *Public Works*, Vol. 50, p. 278, April 2, 1921.

Value of material investigated and results given.

"Effect of Cal on Corrosion," by J. C. Witt, *Concrete* (CMS), p. 154, February, 1921.

"Effect of Cal Under Rapid Drying Conditions," by J. R. Lapham, *Concrete*, Vol. 18, p. 287, June, 1921.

"Influence of Calcium Chloride on Tensile and Compressive Strength of Portland Cement," by C. R. Platzmann, *Zement*, Vol. 10, p. 499, October 6, 1921. Abstract, *Chimie et Industrie*, Vol. 7, p. 943, May, 1922. *Chemical Abstracts*, Vol. 16, p. 2586, 1922.

"Industrial Chemistry Problem Relative to Treatment of Cement (Influence of Addition of Calcium Chloride on Strength of Portland Cement)," by C. R. Platzmann, *Zement*, Vol. 11, pp. 137, 151, 1922. *Chimie et Industrie*, Vol. 8, p. 614, 1922. *Chemical Abstracts*, Vol. 16, p. 4318, 1922.

Calcium chloride (2.4 to 5 per cent) added to mixing water to hasten setting and prevent shrinkage. Tensile and compressive strengths tabulated with different percentages of $CaCl_2$. Increased constancy of volume and generation of heat during setting. Concrete containing calcium chloride less readily attacked by gases which in presence of water form H_2SO_3 and H_2SO_4.

"Calcium Chloride and Cement," by F. Killig, *Zement*, Nos. 45 to 48, 1922. *Chem. Zentr.*, Vol. 94, p. 462, 1923.

Use of calcium chloride up to 7 per cent added to cement in mixing water superior to grinding with cement.

"Calcium Chloride in Concrete Highway Construction," by Piepmeier and Clemmer, *Engineering News-Record*, Vol. 88, p. 409, March 9, 1922.

Laboratory and field tests indicate accelerated setting and more economical curing method than usual practice.

"Calcium Chloride in Concrete," *Concrete*, Vol. 20, p. 176, April, 1922.

Reduces time of set and may prevent freezing before setting. Not recommended in reinforced concrete exposed to extreme moisture.

"Use of Calcium Chloride as Protection Against Freezing of Concrete," by Cottringer and Kendall, *Concrete*, p. 150, April, 1923.

Tests made by Dow Chemical Co., Midland, Mich.

"Comparative Bonding Strength of Portland Cement Mortar," by J. R. Lapham, Pamphlet by Cal Chemical Co., Hagerstown, Md.

"How to Cure Concrete," Booklet published by Dow Chemical Co., 1923.

Use of "Dowflake" calcium chloride, economies, method of patching, quantity, application, etc.

"Strength of Cal Mortar in Laying Brick Work," *Concrete*, Vol. 22, p. 231, June, 1923.

Tensile, compressive, and bond tests of mortar, using Hytex brick with 5 per cent Cal added to mortar. Increase in strength found over mortar without Cal.

"Effect of Accelerators on Reinforcing Steel," *Engineering and Contracting*, Vol. 60, p. 202, July 25, 1923.

Steel in 1:2:4 concrete and 1:3 mortar specimens examined by the U. S. Bureau of Standards after outdoor storage for 5 or 6 years. Tests also made using metal lath in slabs. Corrosion of metal due to calcium chloride was not serious nor of progressive nature when metal was completely embedded. Pockets near reinforcing should be avoided.

"Report of Cooperative Series of Tests on Accelerators," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part I, p. 223 (1923). Abstract, *Engineering and Contracting*, Vol. 60, p. 358, August 22, 1923.

Tests made using different accelerators, by U. S. Bureau of Standards, Lehigh Portland Cement Co., City of Philadelphia, Lewis Institute, Hydro-Electric Power Commission, Pennsylvania State Highway Commission, Delaware State Highway Commission, and New Jersey State Highway Commission.

"Effect of Curing Methods on Concrete Roads," by H. J. Kuelling, *Engineering News-Record*, Vol. 91, p. 466, September 20, 1923.

Tests of methods of curing road slabs to determine effects on wear and transverse strength. Coverings of sodium silicate, calcium chloride, hay, straw, and dirt used.

"Twelve-Hour Compressive Strength Tests," *Municipal Improvements* (Canada Cement Co., Montreal), p. 24, July, 1923.

Results of tests on 1:1 to 1:3 standard sand mortars, with and without calcium chloride up to 5 per cent by weight of cement, and different temperatures of mixing water.

"An Investigation in the Use of Calcium Chloride as a Curing Agent and Accelerator of Concrete," by H. F. Clemmer and Fred Burggraf, *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 296 (1923). *Engineering News-Record*, Vol. 91, p. 143, 1923.

Over 500 slabs, 30 by 12 by 8 in., and 6 by 12-in. cylinders made of 1:2:3½ concrete cured in various ways. Slabs cured by spreading 1 to 3 lb. of dry calcium chloride per square yard had higher modulus of rupture than ordinary curing which enables use of concrete sooner than ordinarily; lumps detrimental. Illinois Highway Specifications require 2½ lb. of calcium chloride flakes spread uniformly on each square yard 6 to 8 hours after concrete is laid. Solution of calcium chloride not sufficient; materials must not be applied during rain, but rain 2 or 3 hours after application will do no harm. Calcium chloride, not more than 2 per cent by weight of cement, may be dissolved in mixing water for use in cold weather, but is not to be used in reinforced concrete, nor near electric railroad crossing.

"Devices for Application of Calcium Chloride in Road Work," *Engineering and Contracting*, Vol. 61, p. 226, 1924.

Describes two devices for spreading calcium chloride.

DISCUSSION

Mr. Lagaard.

MR. M. B. LAGAARD[1] (*presented in written form by F. E. Richart*).—The use of calcium chloride and other similar admixtures in obtaining higher strengths and more rapid hardening of concrete has attracted marked attention recently, although it has been used in this connection since about 1888. It has been interesting to the writer to note that the use of a foreign material as an admixture in concrete seems to make a peculiar appeal to a great many architects and engineers. The feeling that the addition of such a material is necessary as a safeguard to the quality of the concrete stands out, in the writer's experience, with undue importance. Positive proof that the quality of the materials, the amount of water, the manner of mixing and curing, etc., will be responsible for 300 per cent variation in the strength is not one-half so startling, nor easily accepted, nor well remembered as the announcement that a 15 per cent gain can be had by the use of a certain compound.

The true economic value of the use of such material must be given careful consideration when these results are analyzed.

The conclusions brought out by Mr. Abrams' paper reveal a number of interesting points:

> *Conclusion No. 1.*—Calcium chloride and the admixtures containing calcium chloride when used within certain limiting percentages gave increased strength to concrete.
>
> *Conclusion No. 4.*—................ Beyond a certain "critical" percentage further additions produced a reduction in strength as compared to similar concrete without admixtures.
>
> *Conclusion No. 7.*—The addition of calcium chloride in amounts less than the "critical" percentage produced an increase in concrete strength that was practically constant at all ages ....
>
> *Conclusion No. 8.*—The increase in strength due to the addition of 2 per cent of commercial calcium chloride was practically negligible for a 1:7 mix and increased with the cement content up to a 1:4 mix ....
>
> *Conclusion No. 11.*—The effect of commercial calcium chloride on the strength of concrete .... was slightly greater in concrete cured in the air of the laboratory than concrete cured in water or in the moist room.

These conclusions agree in general with the results of a series of tests made at the Experimental Engineering Laboratories, University of Minnesota, under the direction of the writer by Mr. A. S. Levens

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Mr. Lagaard. and presented as a thesis for a Master's degree in Engineering. Th tests in this series were confined to 1:3 mortar briquettes with from 2 to 5 per cent of calcium chloride used. The results show, as in conclusion No. 1, that the strength increases with the use of small percentages of calcium chloride and that beyond a certain amount the strengths begin to fall off. (Conclusion No. 4.)

It was also found that the increase was constant at the ages of 3, 7, and 28 days for moist-air curing (Conclusion No. 7), but that this was not true for air curing (Conclusion No. 11). Here a very marked increase was found at 3 and 7 days while at 28 days the difference was very much less. That is, the air-cured calcium chloride specimens showed very high strengths at 3 and 7 days, almost equivalent to the 28-day results while the moist cured specimens with calcium chloride showed the same gradual increase from 3 to 28 days as those without.

The effect of calcium chloride on the shrinkage was also investigated. These tests were made by J. R. Garzon, a senior student in civil engineering. A comparison was made between specimens without calcium chloride and specimens with 2 per cent of calcium chloride and it was found that the shrinkage of the specimens containing calcium chloride was about 70 per cent greater at 28 days than that of the specimens without calcium chloride. This introduces a very serious objection to the use of this material as the effect of shrinkage has already been brought to the attention of the profession.

In summary, the results presented by Mr. Abrams have brought out the fact that calcium chloride does not produce an appreciable increase in strength in the usual construction mixes and consistencies for building construction. For roads, a considerable increase can be had.

They also show that an excessive amount of this material will result in an actual weakening of the concrete instead of a strengthening, which condition must be continually guarded against if calcium chloride is used.

On the other hand, its value as an accelerator for hardening for roads as well as buildings is important. If Mr. Abrams' data is plotted it is shown that a concrete suitable for road construction, having a strength of 3200 lb. per sq. in at 21 days will attain the same strength at about 14 days when calcium chloride is used. This indicates a considerable saving in the time during which the completed road must be protected from the traffic. Similarly, for building construction, 14-day strengths can be obtained in about 10 days, which will mean that the forms can be removed at an earlier period.

Mr. Humphrey.

MR. RICHARD L. HUMPHREY.[1]—Does the use of calcium chloride increase the required amount of mixing water?

Mr. Abrams.

MR. D. A. ABRAMS.—In our tests approximately the same quantity of water (or calcium chloride solution) was used for the different percentages of calcium chloride. Essentially the same plasticity as measured by the flow test was obtained immediately after the concrete was mixed. However, the addition of calcium chloride caused the concrete to stiffen quickly and consequently more water would be needed to maintain the same consistency after any considerable period of time; the amount necessary to add would depend on the time.

These tests showed that air-cured concrete was *relatively* more benefited by the addition of calcium chloride than concrete cured in a moist condition. It should not be understood, however, that this means that the strength is higher; the air-cured concrete always gave lower strengths, but the *relative strength* was greater for air-cured concrete when calcium chloride was used.

Mr. Spackman.

MR. HENRY S. SPACKMAN.[2]—Is there any explanation for the fact that calcium chloride did not seem to affect the lean 1:7 mix as it did the rich mixes?

Mr. Abrams.

MR. ABRAMS.—I have no explanation, nor do I know why it affects any of them. It is quite clearly brought out that the effect is very much less pronounced in the leaner and wetter mixtures than in the more normal and the richer mixtures. A question was asked with reference to the mixtures used in the tests made outdoors at low temperatures. I find that it is a 1:5 mixture and the tests were made at ages of 1 to 28 days as shown by the diagram. This proportion may be considered an average concrete mixture.

Mr. Libberton.

MR. J. H. LIBBERTON.[3]—The discussion has been largely on the effect of calcium chloride on the early strength of concrete, but there is another angle from which to view this material, namely, its action in accelerating the early hardening of concrete, especially concrete floors. This effect takes place considerably before any test could be made on the mortar from the standpoint of its tensile or compressive strength. The best indication of the efficiency of calcium chloride when used in this manner is the fact that workmen are inclined to object to its use because of the necessity of extraordinarily fast finishing.

There is also the possibility that the use of calcium chloride increases the density of the concrete, and perhaps some attention should be given to this angle of the problem as well.

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[2] Consulting Engineer, Pike County, Pa.

[3] Sales Engineer, General Chemical Co., New York City.

Mr. Greenman. MR. R. S. GREENMAN.[1]—I believe Mr. Abrams called attention to the fact that the critical percentage of calcium chloride was receding at the three-year period. Now I am wondering if he should consider the strength of concrete, or the constancy of strength of concrete, as a criterion of soundness, just how far that critical percentage can recede in the peiod of five, seven, or ten years without having a really critical effect on the soundness of the concrete. I know that it is hardly fair to ask Mr. Abrams to forecast this until he gets further results; at the same time I think that that effect should emphasize the need of observing caution before proceeding too far with the use of calcium chloride. If this record of critical percentages is going to keep on receding, sooner or later it is going to have the effect of making the concrete unsound when a critical percentage has been passed.

Mr. McMillan. MR. F. R. MCMILLAN.[2]—I am impressed by this discussion that the main point of this paper is being overlooked. It seems to me that as is pointed out in Mr. Lagaard's written discussion here we are quibbling about a small percentage of increased strength due to the addition of some ingredient when, by proper selection of the water-ratio or treatment of the materials, we can get several times that amount of increased strength. We are discussing these small percentages, when the paper of Mr. Abrams has shown that changing the water-ratio a few quarts to the bag of cement made a difference in the percentage of strength gained several times that made by the addition of any amount of calcium chloride.

Mr. Abrams. MR. ABRAMS.—I should like to take a moment to point out that in cold-weather work too much dependence should not be placed on the use of chemical admixtures for increasing the strength of concrete. They may have some effect, but the old-fashioned method of heating the water and heating the aggregates, if necessary, is much more dependable and certain of results. The increase in strength due to calcium chloride is a desirable factor, but we must not forget that low temperatures still produce concrete of low strength at early ages.

Now a few words with reference to Mr. Greenman's remarks. While it is true that the critical percentage seems to go to somewhat lower values with later ages, I do not believe we are justified in concluding that that is the source of ultimate danger in concrete. It is not entirely clear that this represents a permanent tendency, nor does it affect the fact that even at the later periods we do get considerable strength from the calcium chloride at normal temperatures.

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[2] Associate Engineer, Structural Materials Research Laboratory, Lewis Institute, Chicago.

Mr. Hollister. MR. S. C. HOLLISTER.[1]—I should like to ask Mr. Abrams what advantage there is in mixing calcium chloride into a concrete or mortar mixture.

Mr. Abrams. MR. ABRAMS.—Well, that is a very pertinent question. The advantage depends somewhat on the conditions, mixtures, etc., with which you are working. In other words we do not find the same advantages in all cases. It was pointed out that an increase occurs in the early strength of most concrete. If the early strength is of no importance, calcium chloride is not advantageous. In other words, in the great bulk of concrete work, we are far more interested in what occurs at 28 days or 1 year or 10 years than we are in what occurs at 2 or 3 days. Under those conditions, there is obviously little advantage in adding calcium chloride. We must bear in mind that calcium chloride costs something, and we know that any required strength of concrete can be produced in a great many different ways with varying effects on cost. We can either wait for it to get stronger by the lapse of time, or we can improve the curing conditions or improve the grading of the aggregate or use more cement or exercise more control in the mixing water or do a little more work in placing it, or almost any combination of these factors, so that it is altogether a question of economy; if it is more convenient and costs less where early strength is important, we can gain some advantage by using calcium chloride. The best way is to use commercial calcium chloride rather than to depend on some other material which has calcium chloride as a base, but in which only the amount of calcium chloride is the measure of its effect.

Mr. Mattimore. MR. H. S. MATTIMORE.[2]—In discussing the use of accelerators in concrete work, one element that has to be considered on a concrete road is the curing period. If a road can be opened for traffic at shorter intervals after placing, the conditions would be more satisfactory both for the traveling public and the engineer. The cost of a 2-per-cent solution of calcium chloride incorporated in the mix is very small, about three cents or less per square yard.

A Member. A MEMBER.—I should like to hear some discussion on the advisability of using calcium chloride in the presence of steel.

Mr. Mattimore. MR. MATTIMORE.—I might say in that connection that we have used calcium chloride incorporated in the mix in concrete road slabs in which steel mesh was used as a reinforcement. Cores were drilled from these slabs about four years after placing, and an examination of the steel did not show any detrimental effect.

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[1] Member of Firm, Light, Hollister and Ferguson, Engineers, Philadelphia, Pa.

[2] Engineer of Materials, Pennsylvania State Highway Commission.

Mr. Libberton.

MR. LIBBERTON.—In construction work generally there have been many cases where the rusting of reinforcing has menaced either the appearance or the strength of a building and with that in mind we have endeavored for some years to determine any cases of rusting where calcium chloride was used in the concrete. While calcium chloride or compounds depending largely upon it for their efficiency have been used in very large quantities during the past ten or fifteen years, we have yet to find a case of rusting in actual construction where calcium chloride was incorporated in the concrete.

Another point is of particular interest and that is the shrinkage of portland-cement concrete in which calcium chloride is used. It is my thought that calcium chloride may have a decided bearing on the shrinkage of portland-cement concrete and I am positive that it has on portland-cement mortar such as is used in the wearing surfaces of concrete floors. Invariably when the percentage of calcium chloride used runs up to the maximum allowed in Mr. Abrams' paper we encounter severe shrinkage cracks and it is my opinion that under no conditions except under very severe temperature conditions should we allow calcium chloride or preparations depending upon it for their efficiency to run over 1 per cent if we are going to always guard against shrinkage cracks in wearing surfaces.

EFFECT OF FINELY DIVIDED LIGNITE COAL ON THE STRENGTH OF CONCRETE

By I. F. Morrison[1] and H. R. Webb[2]

Early in 1922, the writers' attention was called to a sand which was being used in large quantities for making concrete, especially by the Engineering Department of the City of Edmonton, Alberta. The concrete was satisfactory but the A.S.T.M. standard colorimetric test[3] for the sand gave a very dark color and the question was raised as to the quality of the sand. This sand, besides the various minerals usually found in sand, contained small quantities of finely divided lignite coal deposited in numerous pockets in the sand pit at the same time as the sand. The dark color of the caustic soda solution was evidently due to this coal, but it was not known whether the presence of the coal had an effect on the strength of the concrete equivalent to the corresponding color indicated by the tests on the effect of tannic acid conducted by Abrams.[4] Experience tended to show that it had not.

A quantity of the sand was washed and a series of 6 by 12-in. concrete test cylinders of several mixes was made up using unwashed and washed sand, respectively. These cylinders were tested by the writers at the University of Alberta at 28 days. The results showed a gain in strength for the washed sand for all mixes of about 4 per cent.

The writers then decided to make a further study of the matter and in the fall of 1922 outlined the following problem:

1. To determine the effect of various amounts of the coal on the strength, because the amount of coal in the sand as it comes from the pit varies considerably, although the percentage reached is not large; and

2. To investigate the effect of the coal over periods greater than 28 days.

Description of Materials

The sand was obtained from a pit near Perryvale, Alberta, and was washed until the color test gave a light straw color. The sand is of medium to coarse texture, with angular and rounded grains. Over 90 per cent of it is clear transparent quartz coated with iron oxide; with about 5 per cent of feldspathic material, and less than 5 per cent of pebbles and grains of dark shale, coal and other impurities. It is undoubtedly of glacial origin and is made up largely of disintegrated granite. Some of the grains consist of quartz and feldspar.

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[1] Professor of Applied Mechanics, University of Alberta, Alberta, Canada.

[2] Lecturer in Civil Engineering, University of Alberta, Alberta, Canada.

[3] Standard Method of Test for Organic Impurities in Sands for Concrete (C 40 – 22), A.S.T.M. Standards Adopted in 1922.

[4] D. A. Abrams, "Effect of Tannic Acid on the Strength of Concrete," *Proceedings*, Am. Soc. Testing Mats., Vol. XX, Part I, p. 309 (1920).

The coal was obtained from a large pocket which was found in the pit from which the sand came, and was allowed to dry out in the laboratory. The coal is a finely divided lignite float with a high moisture and ash content.

The cement (Canada portland) was tested and found to be satisfactory according to the A.S.T.M. standards, showing a neat tensile strength at 28 days of 830 lb. per sq. in. and a strength with standard sand at 28 days of 335 lb. per sq. in.

The coarse aggregate was a washed and crushed gravel, screened and recombined in the laboratory to give a uniform grading, the maximum size passing a ring 1½ in. in diameter.

From other investigations on concrete with these materials, not reported in this paper, a suitable mix was found to be 1:5.8 and was adopted for this investigation. The important characteristics of the mix were:

Fineness modulus	5.68
Water-Cement Ratio	1.04
Consistency	1.20
Flow	170–180
Average slump	½ in.

PROCEDURE

It was decided to introduce small percentages of coal by weight into the sand just before mixing. The percentages used were 0.05, 0.10, 0.50 and 1.00 per cent. Also cylinders were made with no coal. Sixteen 6 by 12-in. cylinders of each series were made, four to be tested respectively at 28 days, 3 months, 6 months and 1 year; a total of eighty cylinders. All of the coal was weighed out into proper lots on the same day. These lots were done up in paper parcels and were introduced into the sand each time just before mixing.

The concrete was mixed two cylinders at a time and was tamped into the molds with an iron rod pointed at one end and weighing 1 lb. 6 oz. In order that no water should escape, the cylinders were made on flat steel plates and the sheet metal molds were sealed with paraffin wax. The molds were also covered at the top to prevent rapid evaporation. In this way very little water was lost. The cylinders were placed in damp sand until tested.

In testing the cylinders, they were capped top and bottom with a $\frac{1}{8}$-in. layer of plaster of Paris to ensure proper end bearings. The rate of loading was 0.05 in. per minute.

TEST DATA

The results of these tests are shown in Fig. 1. Each point plotted is the average of the results for four cylinders. The range of variation above and below the mean is also shown. The maximum percentage deviation from the average, considering all tests, was 12.3 per cent.

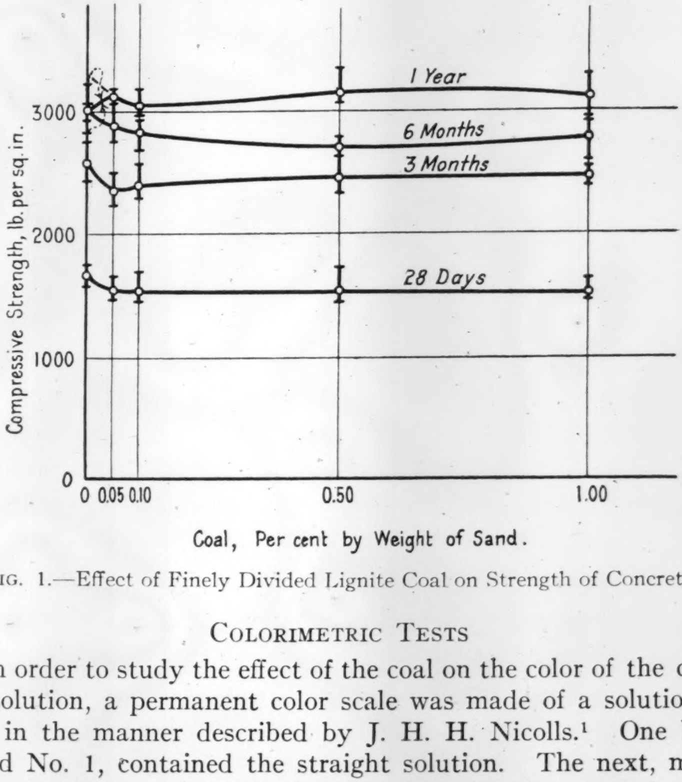

FIG. 1.—Effect of Finely Divided Lignite Coal on Strength of Concrete.

COLORIMETRIC TESTS

In order to study the effect of the coal on the color of the caustic soda solution, a permanent color scale was made of a solution prepared in the manner described by J. H. H. Nicolls.[1] One bottle, marked No. 1, contained the straight solution. The next, marked No. 4, contained some of the solution diluted with an equal amount of water. No. 8 contained some of the diluted liquid of No. 4 again diluted by an equal amount of water, and so on. Thus, a color scale was constructed ranging from an opaque dark brown to a slightly tinted liquid.

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[1] "The Hoffman Potash Test," Summary report No. 454, Mines Branch, Department of Mines, Canada (1916).

A color test was made on the washed sand containing 0.000, 0.005, 0.015, 0.030, 0.050, and 0.100 per cent of coal. The following results were obtained:

COAL, PER CENT	COLOR SCALE NO.	APPROXIMATE COLOR
0.000	24	Light straw; between Figs. 1 and 2[a].
0.005	15	Dark straw.
0.015	12	Brown, like Fig. 5[a].
0.030	9	Dark brown.
0.050	7	Very dark brown.
0.100	(?)	Diluted with equal parts of water, gave a No. 5 color. Very dark brown.

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[a] Report on Organic Impurities in Sands, of Committee C-9 on Concrete and Concrete Aggregates, *Proceedings*, Am. Soc. Testing Mats., Vol. XIX, Part I, p. 321 (1919).

CONCLUSIONS

The conclusions drawn from the results of this investigation are:

1. Small amounts of finely divided lignite coal lower the strength of concrete up to periods of one year. The amount of coal for which this effect was observed was only 0.05 per cent by weight of sand.

2. The effect of amounts of this coal greater than 0.05 per cent is not appreciably more than that for 0.05 per cent, up to amounts of 1.0 per cent by weight of sand.

3. The decrease in strength is about 8 per cent for 0.05 per cent of coal and is not comparable to the decrease in strength due to the presence of organic acid as indicated by the colorimetric test.

4. The colorimetric test cannot be taken as a criterion of inferior quality for sands containing small amounts of lignite coal.

DISCUSSION

Mr. Abrams. MR. D. A. ABRAMS.[1]—We have found in our investigations at Lewis Institute that lignite sands are rather an exception to the well-known general effect of organic materials (as indicated by the colorimetric test with sodium hydroxide) on the strength of concrete. I do not believe, however, that it necessarily means a contradiction in our test methods. The difference appears to be due to the fact that while the lignite in any form responds to the colorimetric test, it apparently is not broken up in mixing to a sufficient extent to make it as detrimental to the strength of the concrete as a similar amount of the more usual organic materials which frequently occur in natural sands. In a great many natural sands in this country we find small amounts of lignite, particularly in the upper Mississippi River sand. Our tests corroborate in every respect the results of Morrison's work. The actual effect of these lignites on concrete mixtures seems to be quite similar to that of like amounts of other inert materials. We have made a great many tests on inert powdered admixtures and find that for the small percentages used in this investigation, only a slight reduction in strength would be expected.

It should not be understood, however, that coal or lignite are entirely harmless in concrete. Such light materials when found in the aggregates are certain to be floated to the surface and consequently will give poor results in concrete exposed to wear or to severe weather conditions.

Mr. Freeman. MR. P. J. FREEMAN.[2]—The subject touched on in this paper is one which causes a great deal of trouble in certain localities. Lignite or decomposed coal, we cannot always tell which, will readily produce a very dark color in sodium hydroxide. In certain localities the mine waste contains sulfuric acid which changes coal to humic acid so that very small quantities will produce colorimetric reactions. Ordinary coal does not produce this reaction unless it has been subjected to very dilute sulfuric acid. In the Pittsburgh district we find these materials in our sands and one part of a barge will not affect the sodium hydroxide, and another sample taken at the same spot which happens to contain the lignite or decomposed coal will produce a black

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[1] Professor, In Charge of Structural Materials Research Laboratory, Lewis Institute, Chicago, Ill.

[2] Chief Engineer, Bureau of Tests and Specifications, Department of Public Works, Allegheny County, Pa.

Mr. Freeman. color, but when tested against Ottawa sand in compression the fact that a ratio of 150 per cent is readily obtained, shows that the strength of the sand has not been reduced. The tendency at first when such conditions are encountered is to reject all material showing a dark color and let the sand men worry, but they have been finding out some things for themselves and they are not disposed to have their material rejected on account of the colorimetric test when the material is undoubtedly satisfactory for use in concrete as shown by the compression tests and the purchaser is put into the position of accepting the material regardless of the colorimetric test in order to keep construction work under way.

Mr. Chapman. MR. CLOYD M. CHAPMAN[1] (*by letter*).—The results of the tests described in this paper are given only in the set of curves in Fig. 1. A study of these curves leads me to doubt the strict justice of the conclusion that small amounts of lignite coal lower the strength of concrete.

The amount of the reduction is slight in all cases, and at the age of one year actual increases in strength are indicated for all proportions of coal admixture.

There are other apparent inconsistencies in the results, such as the constant effect of larger percentages of admixture. One would expect a greater effect from 1 per cent of coal than from one-twentieth of that amount. But at all ages all percentages of admixture give practically the same strengths.

If all of these tests are considered together, the maximum percentage deviation from the average would apparently be well within the usual deviation of compression tests of this character.

It does not appear that these tests have demonstrated that small percentages of finely divided lignite will lower the strength of concrete. Such a conclusion is open to question.

Mr. Morrison. MR. I. F. MORRISON (*Author's closure by letter*).—In reply to Mr. Chapman's discussion, there can be no doubt as to the slight effect of the coal. I have visited several institutions this summer where concrete is being tested. I find that we have given as much care to the details of testing technique as any of them, so I believe the results are accurate enough to detect the effect of the coal.

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[1] Consulting Engineer, New York City.

LABORATORY INVESTIGATIONS OF THE INFLUENCE OF CURING CONDITIONS AND VARIOUS ADMIXTURES ON THE LIFE OF CONCRETE STORED IN SULFATE SOLUTIONS AS INDICATED BY PHYSICAL CHANGES[1]

By Dalton G. Miller[2]

The action on concrete of sodium sulfate (Na_2SO_4) is accompanied by a definite increase of volume, as is that of magnesium sulfate (see Fig. 1), and in this work both the actual increase and the rate of increase, as indicated by length changes, has been used for comparing the behavior of the specimens in the solutions.

It is the practice, in the laboratory, to store the experimental pieces in solutions in earthenware jars, the solutions being changed weekly as it was found that systematic changing was necessary for consistent results. Two by four-inch cylinders have been used, as this size reduced to a minimum the volume of concrete in all jars, thus rendering their care much easier. Moreover, the 2-in. diameter roughly approximates the thickness of the wall of the average size tile used in public ditch work in the Middle West. Attention, however, is called to the fact that these cylinders, while small, are made of concrete and not mortar, although in none of them has there been used an aggregate coarser than $\frac{3}{8}$ in.

The cylinders were made in batches of nine, each series consisting of 45 made on five different days. All five series of any group were made the same week, the order of making being changed daily so that for the week it was the same for all series.

The cylinders as made all had a relative consistency of 1.00, giving a slump of $\frac{1}{2}$ to 1 in. by the standard 12-in. slump cone with a 4-in. top and 8-in. base and having a relative flowability of about 112 on the laboratory flow table using a 2-in. cone with a 3-in. top and 6-in. base. This is the consistency meant wherever reference is made to "normal consistency" in connection with these 2 by 4-in.

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[1] University of Minnesota *Paper No. 480*, Journal Series. This paper is based on experiments at the drain tile laboratory, University Farm, St. Paul, Minn., conducted by the Department of Agriculture of the University of Minnesota, the Department of Drainage and Waters of the State of Minnesota and the U. S. Department of Agriculture. These experiments are designed principally to aid in the general improvement of the quality of farm drain tile and particularly to develop tile that will endure under all soil conditions.

[2] Senior Drainage Engineer, U. S. Department of Agriculture.

concrete cylinders. The mix in all cases was 1:3 by volume with the weight of cement assumed at 100 lb. per cu. ft. Each batch was mixed by hand at least $1\frac{1}{2}$ minutes dry and 2 minutes after adding the water. Each nine-cylinder batch of the laboratory standard cylinders contains 950 g. of Universal and Northwestern States cement passing all standard physical tests and previously thoroughly mixed in four-bag lots, 370 g. (8.25 per cent) of distilled water and 3531 g. of mixed Minnesota aggregate separated for each screen size and recombined for each batch. (For further details of quantities of materials in all series see Table II.) The materials, after mixing, were tamped in three 3-gang brass molds in four layers, each layer being tamped 20 times with a pointed steel rod $\frac{3}{8}$ by 15 in. Round-head brass screws 1 in. long were set in neat cement in the ends of

TABLE I.—SCREEN ANALYSIS AND QUANTITIES OF AGGREGATE FOR NINE-CYLINDER BATCH.

	PER CENT	COARSER THAN	PER CENT	AMOUNT REQUIRED, G.
Passing $\frac{3}{8}$-in.	100	$\frac{3}{8}$-in.	0	....
" $\frac{3}{8}$-in., retained on No. 4	43.7	No. 4	43.7	1543
" No. 4, " " No. 8	20.0	No. 8	63.7	706
" No. 8, " " No. 16	11.9	No. 16	75.6	420
" No. 16, " " No. 30	11.9	No. 30	87.5	420
" No. 30, " " No. 50	9.4	No. 50	96.9	332
" No. 50, " " No. 100	2.7	No. 100	99.6	110
" No. 100	0.4	....	....	....
Fineness modulus =		4.67	467.0	3531

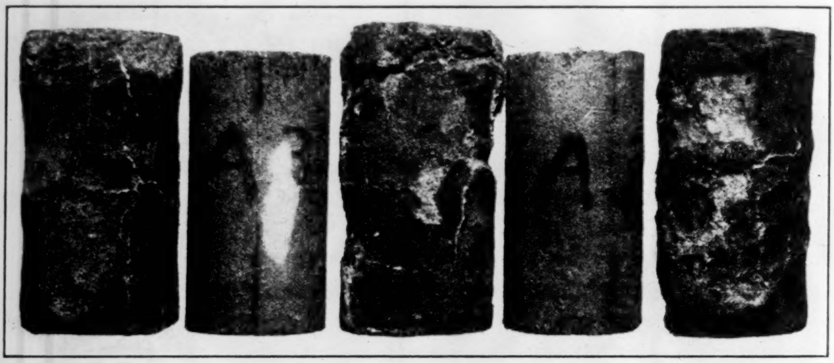

FIG. 1.—Showing the Increase of Volume of Three Standard Ottawa-Sand Cylinders after Long-Time Storage in 1-per-cent Solutions of Magnesium Sulfate ($MgSO_4$), as Compared with Two Cylinders from the Same Lot Stored in Distilled Water.

three cylinders, measurements between screw heads being the basis for recording change of volume. The other six cylinders were left with blank ends, these being used in the various compression tests.

Compression tests were made in a 50,000-lb. Riehlé machine using a bottom spherical bearing block. All cylinders, unless otherwise noted, were tested wet. The absorption results are based on the standard A.S.T.M. absorption test for drain tile.[1]

TABLE II.—MATERIALS USED IN EACH BATCH OF NINE 2 BY 4-IN. PORTLAND-CEMENT-CONCRETE CYLINDERS IN SERIES 28 - 32 AND 41 - 65.

Series No.	Admixture				Cement Used, grams	Quantity of Distilled Mixing Water		Aggregate Weight, g.
	Kind in Each Series	Weight, lb. per cu. ft.	Quantity					
			Weight, grams	Per Cent by Weight of Cement		CC.	Per Cent	
28	No Admixture	..	....	..	950	370	8.25	3531
29	" "	..	....	..	"	"	"	"
30	" "	..	....	..	"	"	"	"
31	" "	..	....	..	"	"	"	"
32	" "	..	....	..	"	"	"	"
41	No Admixture	..	....	..	950	370	8.25	3531
42	Volcanic Ash	53	23.75	2.5	"	383	8.50	"
43	" "	..	47.5	5	"	396	8.75	"
44	" "	..	95.0	10	"	412	9.00	"
45	" "	..	190.0	20	"	467	10.00	"
46	No Admixture	..	....	..	950	370	8.25	3531
47	Ironite	180	47.5	5	"	374	"	"
48	"	..	190.0	20	"	385	"	"
49	Calcium Chloride, C.P.	..	38.0	4	"	384	8.50	"
50	Cal	40	38.0	4	"	373	8.25	"
51	No Admixture	..	....	..	950	370	8.25	3531
52	Alkagel "A"	70	14.25	1.5	"	382	8.50	"
53	" "	..	28.5	3	"	395	8.75	"
54	Water Gas Tar	..	47.5	5	"	352	7.77	"
55	" " "	..	190.0	20	"	324	6.93	"
56	No Admixture	..	....	..	950	370	8.25	3531
57	Hydrated Lime, High Lime	40	47.5	5	"	385	8.50	"
58	" " " "	..	95.0	10	"	400	8.75	"
59	" " High Magnesium	40	47.5	5	"	385	8.50	"
60	" " " "	..	95.0	10	"	400	8.75	"
61	No Admixture	..	....	..	950	370	8.25	3531
62	Blast-Furnace Slag	89	47.5	5	"	379	8.37	"
63	" " "	..	95.0	10	"	389	8.50	"
64	" " "	..	190.0	20	"	409	8.75	"
65	" " "	..	380.0	40	"	450	9.25	"

The aggregate used in all cylinders came from the J. L. Shiely pit, Snelling Avenue and Great Northern tracks, St. Paul, Minn. The unit room dry weight of the aggregate as used was 124 lb. per cu. ft. It passed all standard physical tests including a test for shale, which showed less than 0.4 per cent by volume. The screen analysis and quantities of aggregate per batch are given in Table I.

Early in the work in the laboratory it was found that increasing the strength of either sodium or magnesium sulfate solutions beyond

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[1] Standard Specifications for Drain Tile, 1921 Book of A.S.T.M. Standards.

1 per cent did not materially accelerate the action on concrete. It was found, though, that concrete specimens, however thoroughly cured in water, were least resistant if at no time allowed to dry and harden in the air previous to storing in the test solutions. Except as indicated, all cylinders in this work were cured 24 hours in the moist closet, 20 days in distilled water and then stored directly in the solutions. The effect of so treating the specimens has been to subject them when lowest in resistance to the action of the solutions, and in this way very greatly to accelerate the results. The solution mentioned above, namely, the 1-per-cent solution is 1 per cent by weight on an anhydrous basis. This is nearly equivalent to 2 per cent on the basis of ordinary dry salt.

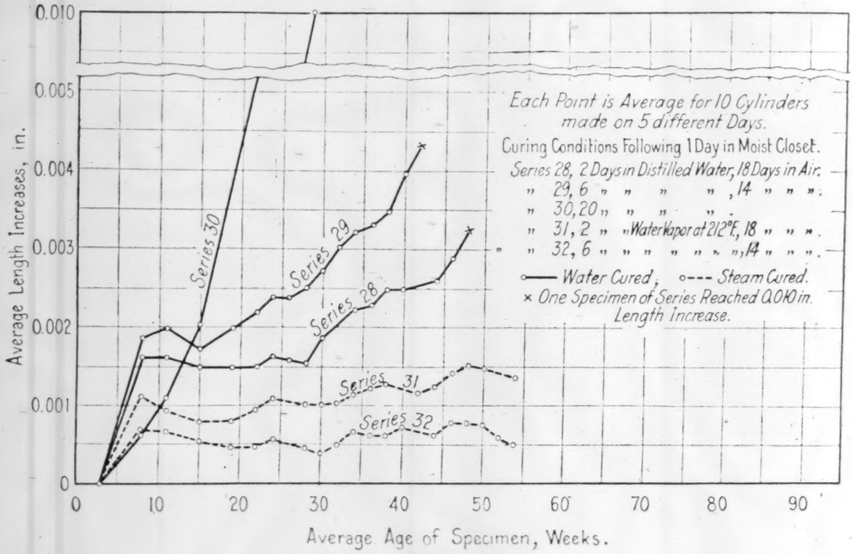

FIG. 2.—Influence of Curing Conditions on Change of Volume of 2 by 4-in. Portland Cement-Concrete Cylinders Stored in 1-per-cent Solutions of Na_2SO_4. Series 28 – 32.

This is indicated in a general way in Table V and Figs. 2 and 3 showing the results of variations of curing conditions in Series 28 to 32. It will be noted that compression tests at one year of the water-cured Series 28 to 30 were most favorable for those series longest in air. It is also interesting to note in this same group that the steam-cured specimens in Series 31 and 32 made a far better showing than did any of the water-cured specimens.

By "Life in Weeks" as used in Tables III and V and in the various figures, is meant the average time required for a group of ten

2 by 4-in. cylinders to show an increase in length of 0.01 in. In previous experiments with cylinders stored in magnesium sulfate solutions it has been found that such a length change indicates a loss in normal strength of 50 per cent, or a little more. In the sodium sulfate solutions the results to date indicate a greater loss of strength than this for the same length change, the average strength ratio for all series shown in Table II that have reached this length being 29.6 per cent or a loss of 70.4 per cent. It will be noted in Table III that for the same length change the strength ratios are quite uniform regardless of the length of time required for the increase.

TABLE III.—STRENGTH RATIO OF 2 BY 4-IN. CONCRETE CYLINDERS WHEN TESTED FOR COMPRESSION AT TIME OF LENGTH INCREASE OF 0.01 IN. AFTER STORAGE IN 1-PER-CENT SOLUTIONS OF SODIUM SULFATE (NA_2SO_4).

Each result is the average for ten or more cylinders made on five different days.

Series No.	Life in Weeks (Time Required to Increase in Length 0.01 in.)	Strength Ratio —Per Cent of Strength of Comparable Cylinders Stored in Tap Water	Series No.	Life in Weeks (Time Required To Increase in Length 0.01 in.)	Strength Ratio —Per Cent of Strength of Comparable Cylinders Stored in Tap Water
30	28.5	28.5	59	33.9	27.3
42	31.6	28.9	60	32.3	33.4
52	34.0	28.3	61	38.4	32.1
53	28.0	34.6	62	43.0	30.5
56	40.1	24.6			
57	33.3	31.0	Average	33.9	29.6
58	29.3	27.3			

TABLE IV.—COMPRESSION TESTS OF EXPERIMENTAL CYLINDERS OF SERIES 56.

STORED IN TAP WATER					STORED IN 1-PER-CENT SOLUTIONS OF NA_2SO_4					
Specimen No.	Date Made	Date Tested	Age, days	Compressive Strength, lb. per sq. in.	Specimen No.	Date Made	Date Tested	Age, days	Compressive Strength, lb. per sq. in.	Increase in Length, in.
1	Apr. 16, '23	Feb. 11, '24	301	6640	2	Apr. 16, '23	Mar. 5, '24	324	1380	0.0100
5	Apr. 16, '23	Feb. 11, '24	301	.....	3	Apr. 16, '23	Mar. 19, '24	338	1300	0.0096
6	Apr. 16, '23	Feb. 11, '24	301	6920	11	Apr. 17, '23	Feb. 12, '24	301	1680	0.0095
10	Apr. 17, '23	Feb. 11, '24	300	5560	12	Apr. 17, '23	Feb. 26, '24	315	1360	0.0097
14	Apr. 17, '23	Feb. 11, '24	300	7850	20	Apr. 18, '23	Nov. 30, '23	226	2150	0.0101
15	Apr. 17, '23	Feb. 11, '24	300	7850	21	Apr. 18, '23	Dec. 19, '23	245	1660	0.0101
19	Apr. 18, '23	Feb. 11, '24	299	5810	27	Apr. 19, '23	Jan. 31, '24	287	1060	0.0099
23	Apr. 18, '23	Feb. 11, '24	299	5950	30	Apr. 19, '23	Jan. 17, '24	273	2030	0.0098
24	Apr. 18, '23	Feb. 11, '24	299	7190	38	Apr. 20, '23	Jan. 4, '24	259	2222	0.0098
28	Apr. 19, '23	Feb. 11, '24	298	5970	39	Apr. 20, '23	Feb. 11, '24	297	1460	0.0106
32	Apr. 19, '23	Feb. 11, '24	298	7240						
33	Apr. 19, '23	Feb. 11, '24	298	6010	Average			286	1630	0.0099
37	Apr. 20, '23	Feb. 11, '24	297	6040						
41	Apr. 20, '23	Feb. 11, '24	297	6170						
42	Apr. 20, '23	Feb. 11, '24	297	7680						
Average			299	6630						

As a basis for comparing the general uniformity of the change-of-volume method, as indicated by increase in length of the cylinders, with compression tests, the data in Table IV are presented. The figures in this table are taken from the laboratory note book. The average length of time for the cylinders to increase in length 0.0099 in. was 286 days. The maximum departure from this average was 21.0 per cent. The average compressive strength of the fourteen cylinders in tap water at 42.7 weeks was 6630 lb. per sq. in., the departure from the average being 19.2 per cent. The average strength of the ten cylinders from the 1-per-cent sodium sulfate solutions at 40.1 weeks was 1630 lb. per sq. in.; the departure from the mean being 36.2 per cent. Due partly to the fact that the ends of the cylinders stored in the sulfate solutions become quite soft and crumble badly, compression tests of such cylinders are never as satisfactory as of normal ones even after most careful capping with plaster of Paris. Consequently the change-of-volume method probably actually indicates the true condition of these cylinders with greater accuracy than do the compression tests.

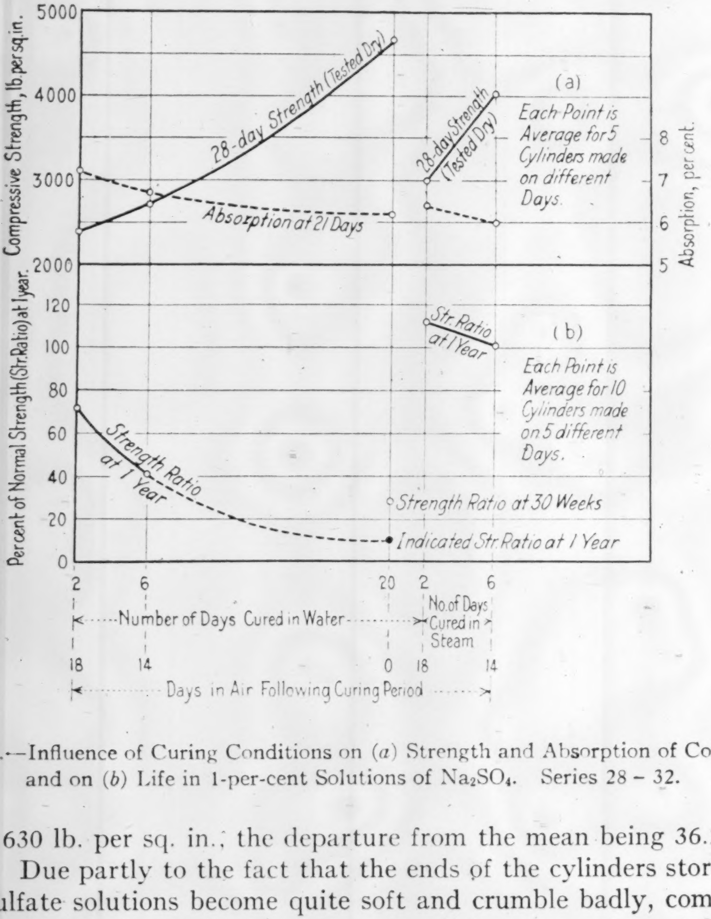

FIG. 3.—Influence of Curing Conditions on (*a*) Strength and Absorption of Concrete and on (*b*) Life in 1-per-cent Solutions of Na_2SO_4. Series 28 – 32.

Curing Conditions of Series 28 to 32 and Brief Description of Admixtures Used in the Other Series

Series 28–32. Variable Curing Conditions.

Series 28. Moist closet 1 day, distilled water 2 days, air 18 days.
Series 29. Moist closet 1 day, distilled water 6 days, air 14 days.
Series 30. Moist closet 1 day, distilled water 20 days, air 0 days.
Series 31. Moist closet 1 day, steam at 212° F., 2 days, air 18 days.
Series 32. Moist closet 1 day, steam at 212° F., 6 days, air 14 days.

Series 41–45. Volcanic Ash.—The ash used is a siliceous material from Sheridan County, Nebraska, insoluble in cold water, free from organic impurities, with the following screen analysis. It was mixed in the batch dry with the cement.

Screen Sizes	Per Cent
Passing No. 30, retained on No. 50	0.0
Passing No. 50, retained on No. 100	0.4
Passing No. 100, retained on No. 200	8.4
Passing No. 200	91.2
	100.0

Series 46–50. Ironite, $CaCl_2$, Cal.—Ironite is the trade name for a powdered waterproofing product manufactured by the Ironite Co., Tinley Park, Chicago. The recommended method of use is by brush coat, or coats, applied to the surface of the concrete after the removal of the forms. In Series 47 and 48 it was mixed dry with the cement and aggregate. Such use of this material as an admixture, so far as is known, is not advocated by the manufacturers.

Calcium chloride, $CaCl_2$, used in Series 49 was a chemically pure product, dissolved in the mixing water.

Cal, used in Series 50, is the trade name for a powdered product manufactured by the Cal Chemical Co., Inc., Hagerstown, Md. Quoting from the U. S. Bureau of Standards, *Technologic Paper No. 174*, "Cal is a material obtained by pulverizing the dried or undried product resulting from a mixture of either quicklime or hydrated lime, calcium chloride and water."

Series 51–55. Alkagel and Water-Gas Tar.—Alkagel is the trade name for a colloidal product put out by the American Algin Products Co., Duluth, Minn. It was dissolved in the mixing water and added to the batch.

The water-gas tar was obtained from a St. Paul gas plant near Washington St., across the Mississippi River from the campus of the University of Minnesota. After the water was partially mixed into the batch the water-gas tar was added and mixed in.

TABLE V.—INFLUENCE ON STRENGTH, ABSORPTION AND RESISTANCE TO 1-PER-CENT SOLUTIONS OF SODIUM SULFATE (NA_2SO_4), OF VARYING THE CURING CONDITIONS OF PORTLAND CEMENT CONCRETE AND OF ADDING VARIOUS MATERIALS TO THE BATCH AS INDICATED BY COMPRESSION TESTS AND CHANGE OF VOLUME OF 2 BY 4-IN. CYLINDERS.

Each result is average for five or more cylinders made on five different days.

Series No.	General Description	Fineness Modulus of Aggregate	Per Cent of Mixing Water	Absorption at 21 Days, per cent	Stored in Water		Stored in Solutions of Na_2SO_4							
					Compression Tests		Compression Tests			Life in Weeks[1]	Cylinders with less than 0.010 in. Increase			
					Age, weeks	Strength, lb. per sq. in.	Age, weeks	Strength, lb. per sq. in.	Strength Ratio, per cent		Age, weeks	Number	Per Cent of Total	Average Length Increase, in.
	SERIES 28–32, CURING													
28	Laboratory Standard Cylinders Cured 2 days in distilled water and air 18 days	4.67	8.25	7.21	1 4 52	.... 2380 5310	52	3830	72.1	....	56	9	90	0.0023
29	Laboratory Standard Cylinders Cured 6 days in distilled water and air 14 days	4.67	8.25	6.71	1 4 52	.... 2720 4570	52	1850	40.5	....	56	8	80	0.0046
30	Laboratory Standard Cylinders Cured 20 days in distilled water	4.67	8.25	6.20	1 4 30	.... 4680 5020	30	1430	28.5	28.5	..	0	0	.....
31	Laboratory Standard Cylinders Cured 2 days in steam at 212° F. and air 18 days	4.67	8.25	6.42	1 4 52	.... 3000 3940	52	4430	112.4	....	56	10	100	0.0013
32	Laboratory Standard Cylinders Cured 6 days in steam at 212° F. and air 14 days	4.67	8.25	5.98	1 4 52	.... 4040 4420	52	4480	101.4	....	56	10	100	0.0001
	SERIES 41–46, VOLCANIC ASH													
41	Laboratory Standard Cylinders	4.67	8.25	5.95	1 4 44	2690 4540 5880	....	....	....	....	52	1	10	0.0043
42	Laboratory Standard Cylinders with 2½ per cent Volcanic Ash	4.67	8.50	6.40	1 4 32.4	2370 4420 4990	31.6	1440	28.9	31.6	..	0	0	.....
43	Laboratory Standard Cylinders with 5 per cent Volcanic Ash	4.67	8.75	6.22	1 4 30.3	2440 4020 5480	....	....	....	....	52	1	10	0.0090
44	Laboratory Standard Cylinders with 10 per cent Volcanic Ash	4.67	9.00	6.34	1 4 46.4	2050 3630 5340	....	....	....	....	52	3	30	0.0057
45	Laboratory Standard Cylinders with 20 per cent Volcanic Ash	4.67	10.00	7.02	1 4	1780 3290	....	....	....	....	52	8	80	0.0016

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[1] By "Life in Weeks" is meant average time required for ten cylinders to increase in length 0.01 in.

TABLE V.—(*Continued*)

Each result is average for five or more cylinders made on five different days.

Series No.	General Description	Fineness Modulus of Aggregate	Per Cent of Mixing Water	Absorption at 21 Days, per cent	Stored in Water		Stored in Solutions of Na_2SO_4							
					Compression Tests		Compression Tests			Life in Weeks[1]	Cylinders with less than 0.010 in. Increase			
					Age, weeks	Strength, lb. per sq. in.	Age, weeks	Strength, lb. per sq. in.	Strength Ratio, per cent		Age, weeks	Number	Per Cent of Total	Average Length Increase, in
	SERIES 46–50, IRONITE, $CaCl_2$, CAL													
46	Laboratory Standard Cylinders	4.67	8.25	5.60	1 4 47	3090 4620 5440	....	....	....	....	52	2	20	0.0062
47	Laboratory Standard Cylinders with 5 per cent Ironite	4.67	8.25	5.77	1 4	3040 4910	....	....	....	....	52	4	40	0.0065
48	Laboratory Standard Cylinders with 10 per cent Ironite	4.67	8.25	6.24	1 4	3030 4130	....	....	....	....	52	9	90	0.0066
49	Laboratory Standard Cylinders with 4 per cent $CaCl_2$	4.67	8.50	7.04	1 4	2720 3970	....	....	....	....	52	8	80	0.0052
50	Laboratory Standard Cylinders with 4 per cent Cal	4.67	8.25	6.19	1 4	2950 4200	....	....	....	....	52	9	90	0.0065
	SERIES 51–55, ALKAGEL, WATER-GAS TAR													
51	Laboratory Standard Cylinders	4.67	8.25	5.14	1 4 47	3200 4760 5315	....	....	....	....	50	4	40	0.0085
52	Laboratory Standard Cylinders with 1½ per cent Alkagel	4.67	8.50	5.74	1 4 34	2990 4150 5660	34	1600	28.3	34.0	..	0	0	......
53	Laboratory Standard Cylinders with 3 per cent Alkagel	4.67	8.75	5.87	1 4 29	3300 4070 4660	28	1610	34.6	28.0	..	0	0	......
54	Laboratory Standard Cylinders with 5 per cent Water-Gas Tar	4.67	7.77	4.71	1 4 28	2420 3980 4520	....	....	....	....	50	1	10	0.0073
55	Laboratory Standard Cylinders with 20 per cent Water-Gas Tar	4.67	6.93	5.72	1 4	1140 2140	....	....	....	....	50	6	60	0.0019

[1] By "Life in Weeks" is meant average time required for ten cylinders to increase in length 0.01 in.

TABLE V.—(*Continued*)

Each result is average for five or more cylinders made on five different days.

Series No.	General Description	Fineness Modulus of Aggregate	Per Cent of Mixing Water	Absorption at 21 Days, per cent	Stored in Water		Stored in Solutions of Na_2SO_4							
					Compression Tests		Compression Tests			Life in Weeks[1]	Cylinders with less than 0.010 in. Increase			
					Age, weeks	Strength, lb. per sq. in.	Age, weeks	Strength, lb. per sq. in.	Strength Ratio, per cent		Age, weeks	Number	Per Cent of Total	Average Length Increase, in.
	SERIES 56-60, HYDRATED LIME													
56	Laboratory Standard Cylinders	4.67	8.25	5.77	1 4 42.7	3370 4590 6630	40.1	1630	24.6	40.1	..	0	0	......
57	Laboratory Standard Cylinders with 5 per cent High-Lime Hydrated Lime	4.67	8.50	5.99	1 4 35.3	3520 4510 5680	33.3	1760	31.0	33.3	..	0	0	......
58	Laboratory Standard Cylinders with 10 per cent High-Lime Hydrated Lime	4.67	9.00	6.74	1 4 33	2860 4440 5640	29.3	1540	27.3	29.3	..	0	0	......
59	Laboratory Standard Cylinders with 5 per cent High-Magnesium Hydrated Lime	4.67	8.50	5.88	1 4 33.1	3170 4620 6490	33.9	1770	27.3	33.9	..	0	0	......
60	Laboratory Standard Cylinders with 10 per cent High-Magnesium Hydrated Lime	4.67	8.75	6.31	1 4 32	3050 4980 5000	32.3	1670	33.4	32.3	..	0	0	......
	SERIES 61-66, SLAG													
61	Laboratory Standard Cylinders	4.67	8.25	5.47	1 4 38	3430 4290 6130	38.4	1970	32.1	38.4	..	0	0	......
62	Laboratory Standard Cylinders with 5 per cent Blast-Furnace Slag	4.67	8.37	5.44	1 4 43	3370 4920 6230	43.0	1900	30.5	43.0	..	0	0	......
63	Laboratory Standard Cylinders with 10 per cent Blast-Furnace Slag	4.67	8.50	5.60	1 4	3110 4710	....	....	....	....	49	8	80	0.0045
64	Laboratory Standard Cylinders with 20 per cent Blast-Furnace Slag	4.67	8.75	5.58	1 4	3460 4600	....	....	....	....	49	10	100	0.0027
65	Laboratory Standard Cylinders with Blast-Furnace Slag	4.67	9.25	5.48	1 4	3230 4340	....	....	....	....	49	10	100	0.0004

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[1] By "Life in Weeks" is meant average time required for ten cylinders to increase in length 0.01 in

Series 56–60. Hydrated Lime.—The hydrated lime used in Series 57 and 58 was a high-lime hydrated lime sold under the trade name of "Chemically Pure" by the Marblehead Lime Co. of Chicago and Kansas City. The hydrated lime used in Series 59 and 60 is what is known as a high-magnesium hydrated lime and is sold under the trade name of "Ivory Finishing Lime." It is the product of the U. S. Gypsum Co. with a plant at Lima, Ohio.

The hydrated lime was mixed dry with the cement and aggregate.

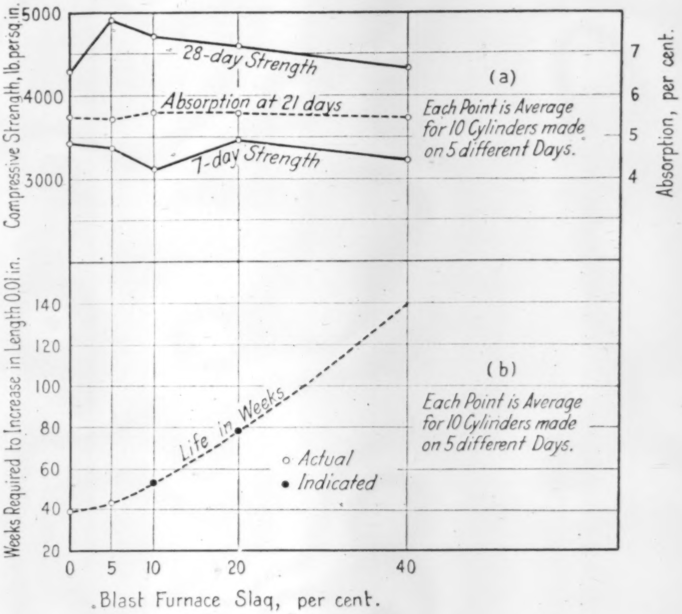

FIG. 4.—Influence of Blast-Furnace Slag on (*a*) Strength and Absorption of Concrete and on (*b*) Life in 1-per-cent Solutions of Na_2SO_4. Series 61 – 65.

Series 61–65. Blast-Furnace Slag.—The slag used in these series was obtained from the Universal Portland Cement plant at Duluth, Minn. Before using, it was ground in a coffee-mill-type grinder in the State Bureau of Mines at the University of Minnesota until it approached the fineness of cement. The mill used was not heavy enough to crush the iron pebbles and these were rejected. The material, after grinding, was screened on Nos. 100 and 200 sieves and recombined in the proportion of 1 part passing the No. 100 and retained on the No. 200 sieve and 5 parts passing the No. 200 sieve. It was mixed dry with the cement and aggregate.

COMMENTS AND CONCLUSIONS

It will be noted in Fig. 2 that the strength ratios at one year of the cylinders in the three water-cured Series 28, 29, and 30, vary in the inverse order of the length of time the cylinders were cured in water and in the same order as the length of the air-storage period. Consequently the lives of the cylinders in the three series eventually will vary in the inverse order of their strength at 28 days. This is shown in Fig. 2 and Table V by such length changes as already have taken place.

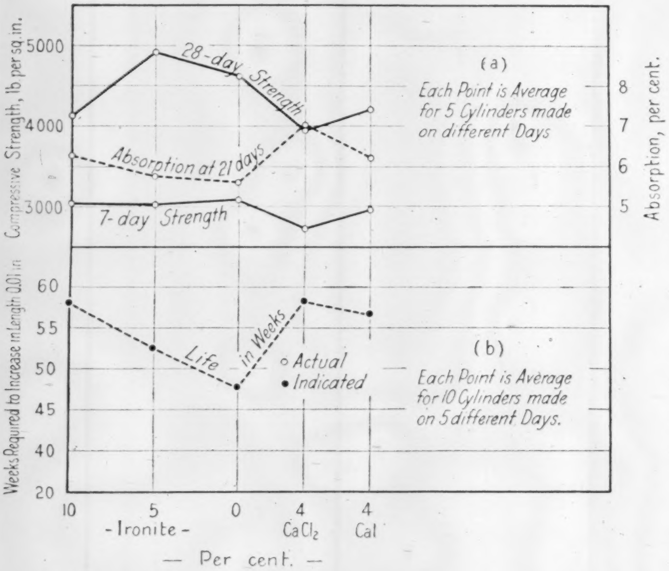

FIG. 5.—Influence of Ironite, $CaCl_2$ and Cal on (*a*) Strength and Absorption of Concrete and on (*b*) Life in 1-per-cent Solutions of Na_2SO_4. Series 46 – 50.

This is significant to the extent that it emphasizes the fact that concrete, regardless of how well cured in water, subsequently must be allowed thoroughly to dry and harden before exposed to the action of sulfate-bearing waters if great resistance to attack is to be expected. It cannot at this time definitely be stated how long this period should continue in order to raise the resistance to the practical limit. It is evident, however, that during the air-storage period, resistance continues to increase for a matter of some weeks.

It will be seen in Fig. 3 and Table V that, after one year in the sulfate solutions, the strength of the steam-cured cylinders in Series

31 and 32 was normal. As may be seen in Fig. 2, the increase of volume of these two series, as indicated by the average length increases, is very much less than for Series 28 and 29 cured for the same time periods in water. Visually the condition of all cylinders at one year in Series 31 and 32 is all that could be desired. It seems fair to assume then that inasmuch as no evident physical deterioration has taken place at one year in the cylinders cured in water vapor, at or near the

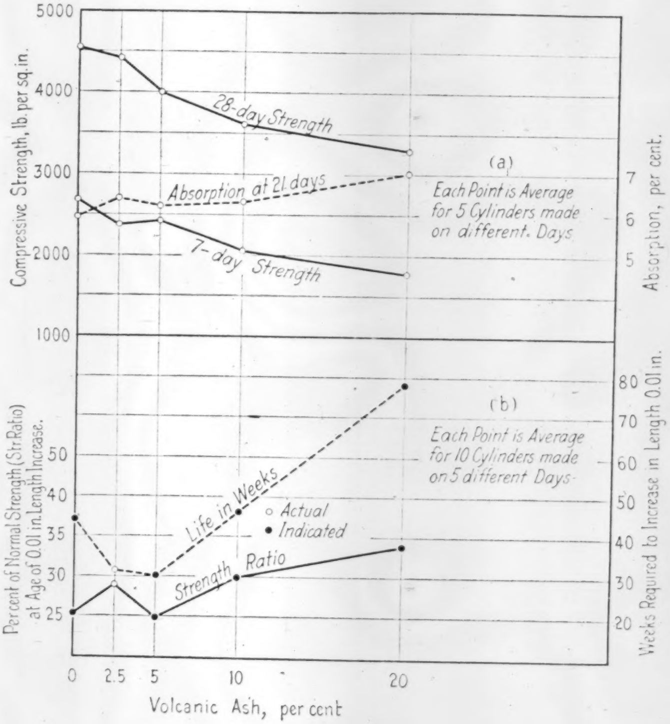

FIG. 6.—Influence of Volcanic Ash on (*a*) Strength and Absorption of Concrete and on (*b*) Life in 1-per-cent Solutions of Na_2SO_4. Series 41 – 45.

normal boiling temperature of 212° F. for water, the resistance of concrete so cured to sulfate-bearing waters is markedly greater than that of water-cured cylinders, all other factors being the same. The actual relative difference and the influence of curing in water vapor at temperatures other than about 212° F. can not be stated at this time, although experiments along this line are under way.

Ordinarily so-called steam-cured concrete drain tile, blocks and other commercial products are cured in a temperature rarely exceeding

100° F., and this type of curing is not to be confused with curing in a temperature near 212° F. such as was done in Series 31 and 32.

The addition to concrete of powdered blast-furnace slag up to 40 per cent of the weight of the concrete apparently had little or no influence on the strength and absorption, although resistance to sulfate waters was increased closely proportional to the quantity of slag added. This is shown in Fig. 4 drawn from data of Series 61–65.

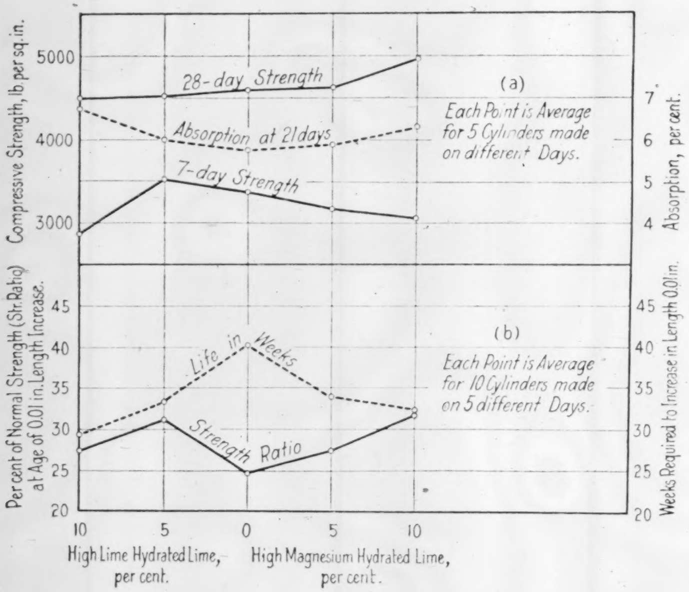

FIG. 7.—Influence of Hydrated Lime on (*a*) Strength and Absorption of Concrete and on (*b*) Life in 1-per-cent Solutions of Na_2SO_4. Series 56 – 60.

Ironite added to concrete in Series 47 and 48 up to 10 per cent of the weight of the cement had but slight influence on the strength and absorption, although the life in the sulfate solutions increased, within the limits used, with the amount of ironite. This is shown in Fig. 5. Adding 4 per cent calcium chloride ($CaCl_2$) to concrete, or 4 per cent of Cal, in Series 49 and 50 increased the life of specimens in sulfate solutions about 20 per cent, as shown in Fig. 5.

The use of a siliceous material in the form of volcanic ash as an admixture in Series 41–45 increased the life of specimens nearly 70 per cent as shown in Fig. 6, when as much as 20 per cent by weight of the cement was added. For the amounts less than 20 per cent the results were negative. The resulting loss in strength due to adding 20 per cent ash was about 30 per cent so that the utility of this material probably is very limited as a means of developing resistance to sulfates.

Both high-calcium and high-magnesium hydrated lime gave negative results in Series 56–60 on the life of concrete in sulfate solutions when used in proportions of 5 and 10 per cent as shown in Fig. 7.

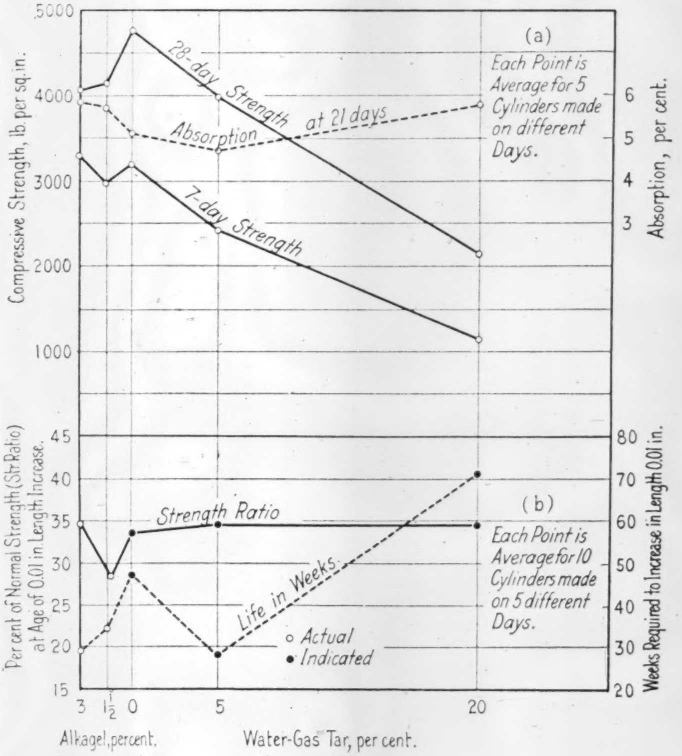

FIG. 8.—Influence of Alkagel and Water-Gas Tar on (*a*) Strength and Absorption of Concrete and on (*b*) Life in 1-per-cent Solutions of Na_2SO_4. Series 51 – 55.

In Series 51–55 the use of Alkagel "A" in the proportions of 1½ and 3 per cent gave negative results in Series 52 and 53 as did water-gas tar in the proportion of 5 per cent in Series 54 as Fig. 8 shows.

Twenty per cent of water-gas tar in the cylinders of Series 55, as shown in Fig. 8, caused more than 50 per cent loss in strength, although, probably due to the water-repellent qualities, the life of the specimens in the sulfate waters was about 50 per cent above that of normal cylinders. With so great a strength loss the use of water-gas tar would scarcely appear to be feasible.

DISCUSSION

Mr. Wig. MR. R. J. WIG.[1]—I would like to ask the author to what he attributes the resistance of the steam-cured concrete compared with the water-cured concrete?

Mr. Miller. MR. D. G. MILLER.—The easiest way to answer that is to say that I do not know. The only thing that we do know is that in the drying of the concrete after the water has been applied during the curing, the resistance increases, and I think that probably you get somewhat the same action in the steam curing, except that it is accelerated. Whether it is the hydration of the silicates, I do not know. It has been suggested that it is a more complete hydration of the silicates and that they are more nearly fixed. I do not know, and candidly, that is something we have been puzzling over, but it seems to be very consistent, because we have never found any exceptions to the conditions, and several series have gone that same way.

Mr. Spackman. MR. H. S. SPACKMAN.[2]—I should like to ask if there is any comparison between the steam-cured cylinders and the ordinary air-cured? You stated that you resorted to water curing in order to accelerate the effect, but you give no results for the ordinary air-cured. How do the ordinary air-cured compare with the steam-cured cylinders?

Mr. Miller. MR. MILLER.—That is something we have been working on. We have several groups of cylinders in which we are trying to determine the value of air curing and trying to fix some sort of limit of time beyond which it is perhaps not worth while to air cure, because I think we all recognize the fact that there is a limit to the value of air curing, because I think it has been the experience of all workers along this line that concrete even cured a long while in air is not entirely resistant to this action, but it is very much increased, and what we are now trying to do is to fix some sort of a practical limit where the maximum benefits will have accrued due to the hardening in air.

I cannot say whether the air-cured approach the steam-cured in their resistance, because those specimens, more completely cured, are very long lived. We have cylinders that will eventually answer that question as nearly exactly as we can answer it, but at the present time

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[1] Vice-President, Celite Products Co., Los Angeles, Calif.

[2] Consulting Engineer, Egypt Mills Post Office, Pike County, Pa.

Mr. Miller. we do not have that data because, as we begin to make the cylinders better and to cure them better, either in steam or air, their lives become very great and it takes a long while to work out all those things. So far I will say this, that within the limits within which we have cured in air, we have not found that there was anything that would indicate they were going to be as completely resistant as the steam-cured, regardless of the time period.

Mr. Pearson. MR. J. C. PEARSON.[1]—I should like to ask the author whether any of the cylinders containing the mixtures of either blast-furnace slag or volcanic ash were subjected to the steam treatment?

Mr. Miller. MR. MILLER.—Since these groups, we have done that very thing, and we have several series where we have subjected them to steam at different temperatures, ranging from 100 to 155° F. and near the boiling point of water, and also subjected them to long-time curing in air, to see what we could develop by such different treatments.

They are not very old yet; it is only a matter of months and as yet they all look the same. It is peculiar though in the change of volume that specimens may run along several weeks or months without showing any increase, and all at once they start up and go very rapidly. I would not say that there had been any encouragement or anything to discourage us, there is simply nothing to show. We did steam-cure specimens with all these admixtures. Some of the results were not very satisfactory because the strength dropped off as soon as we applied steam; others stood up under the steam very satisfactorily but whether there will be less resistance after steaming is a question.

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[1] Assistant to Chemical Engineer, Lehigh Portland Cement Co., Allentown, Pa.

ACCELERATED WEAR TESTS OF CONCRETE PAVEMENTS

By F. H. Jackson[1] and J. T. Pauls[2]

The accelerated wear tests of concrete pavements conducted by the U. S. Bureau of Public Roads, at Arlington, Va., during the past eighteen months, have reached the stage where it is possible to draw fairly definite conclusions from the data so far obtained. The 62 concrete test sections, each 4 ft. wide by about 10 ft. long and constructed in the form of a circle approximately 625 ft. in circumference, have been subjected to approximately 300,000 passages of a solid-rubber-tired truck wheel loaded to 3000 lb. and traveling around the circle over the same path at a speed of 22 miles per hour. Careful observations of the lateral distribution of traffic across actual pavements indicate that about 10 per cent of the total passes over a 6-in. width at the point of greatest concentration. This is based on traffic passing in two directions over an 18-ft. road. On this basis it is estimated that the experimental pavement sections have been subjected to a traffic equivalent to about 1,500,000 two-ton trucks operating at a speed of 22 miles per hour, assuming the distribution indicated by the above observations. In addition, the test sections have been subjected to about 50,000 passages of a solid-rubber-tired wheel loaded with the same weight and equipped with non-skid chains and the same number of passages of a plain rubber-tired wheel. The wheels in this part of the test traveled over a new path. It will be seen, therefore, that the equivalent of an enormous volume of traffic has been put upon the pavement, an amount probably equivalent to several years traffic on the average concrete road.

It was, of course, impossible to reproduce on the test sections in the short space of a year and a half the effect of freezing and thawing which, through a period of years, may weaken actual roads so that they become less resistant to traffic. It was likewise impossible to reproduce the effect of differential expansion and contraction of the thin, rich mortar top and the mass of the concrete, which, caused by wide variations in temperature, may also in time lower the resistance of a pavement. The essential time element is lacking. In these respects, therefore, the test did not duplicate actual conditions, and for this reason the differences in the behavior of the several sections under examination may not be so marked as they normally would have been.

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[1] Senior Assistant Testing Engineer, U. S. Bureau of Public Roads.

[2] Highway Engineer, U. S. Bureau of Public Roads.

PURPOSE AND RESULTS OF THE TEST

The primary object of the test was to determine what relations, if any, exist between the surface behavior of concrete roads under traffic and the various laboratory tests for quality of the aggregates. Incidentally, it was also deemed desirable to determine the relation between the wear as produced by traffic, as well as by laboratory test, and the various physical properties of the concrete, such as crushing strength, transverse strength, modulus of elasticity and absorption. All of these tests were made on the concrete used in each of the 62 test sections.

Specifications for aggregates for concrete pavements are usually drawn to cover the gradation and the quality of the material to be furnished. The gradation or proportion of the various sizes, especially as regards aggregates which are crushed and screened, depends largely on factors that can be controlled, so that the engineer may obtain almost any desired gradation of sizes provided he is willing to insist upon it. The quality of the material, however, can not be fixed in so arbitrary a fashion. Due to the high cost of transportation, the aggregates for any given improvement must generally be found within a relatively short distance of the site of the work. Therefore, as the quality and character of materials varies so greatly in different parts of the country, it follows that many different kinds and types of aggregates must be employed in the construction of concrete roads. All that can be done is to draw specifications in such a way as to insure the use of the best material available for the work. In so doing, however, there is always a minimum limit beyond which it is unsafe to go.

What are the safe test limits for the various kinds of aggregates used in concrete road construction? Do the present limits for wear, strength, etc., insure the selection of safe materials, or, on the other hand, do they unduly add to the cost of construction by setting laboratory requirements too high? These are some of the questions which the accelerated wear tests were designed to answer.

The detailed conclusions which it has been possible to draw from the test are set forth fully at the end of this paper. Outstanding from these conclusions are two facts of major importance. These are:

1. That rubber-tired traffic alone does not appreciably abrade the surface of a concrete pavement.

2. That there is no consistent relation between the results of "tensile-strength-ratio" test for sand, the compression or transverse strength tests, or the Talbot-Jones wear test of concrete, and the wear-resisting properties of concrete pavements.

DESCRIPTION OF THE TEST SECTIONS

The test sections were constructed in the form of a circular concrete pavement approximately 625 ft. in circumference and 4 ft. wide. There were 62 sections, each about 10 ft. long. A general view of the experiment, showing also the stability experiments on bituminous surfaces, is given in Fig. 1. Inasmuch as the only object of this test was to bring out differences in the amount and character of wear or surface disintegration due to traffic, the sections were constructed heavily enough to prevent the possibility of any structural failure. The test sections were laid in two courses. The lower 8-in. course was laid directly on the subgrade, and consisted of 1 : $1\frac{1}{2}$: 3 concrete, using Potomac river sand and gravel as aggregates. A high-grade portland cement passing all of the American Society for Testing Materials requirements was used throughout the experiment. On one side of the circle it was found necessary to construct the test pavement on a fill. The base over this section was further strengthened by the use of a reinforced-concrete T-beam section constructed

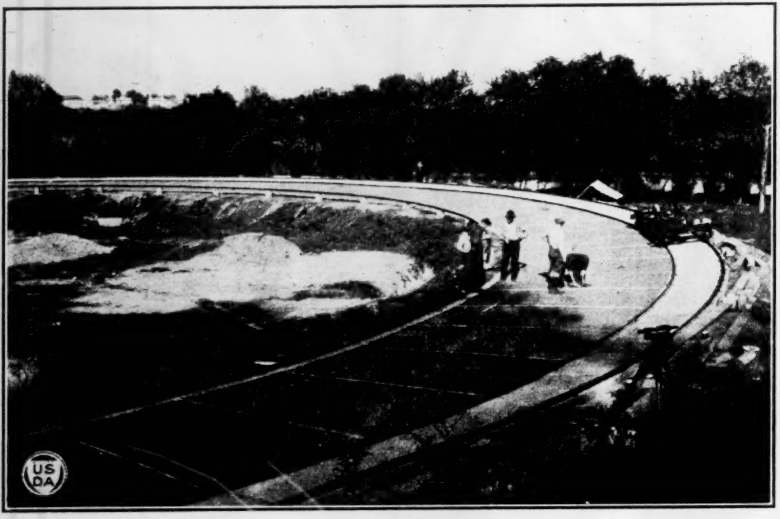

FIG. 1.—General View of Circular Pavement.

with the beams running longitudinally. This design proved entirely adequate and there has been no evidence of failure due to settlement of any test section. The upper course, comprising the test concrete forming each section, was cast directly upon the green concrete base and was 4 in. in depth. The total depth of pavement therefore was in every case at least 12 in. of monolithic concrete. No expansion joints were provided, the concrete in each day's run being finished to a vertical wooden bulkhead which was removed the next day and the fresh concrete deposited directly against that placed the day before. As a result of this procedure construction joint cracks have formed between several of the sections. Additional contraction cracks have also developed in a few places. None of these cracks, however, has affected the stability of the pavement in the slightest degree.

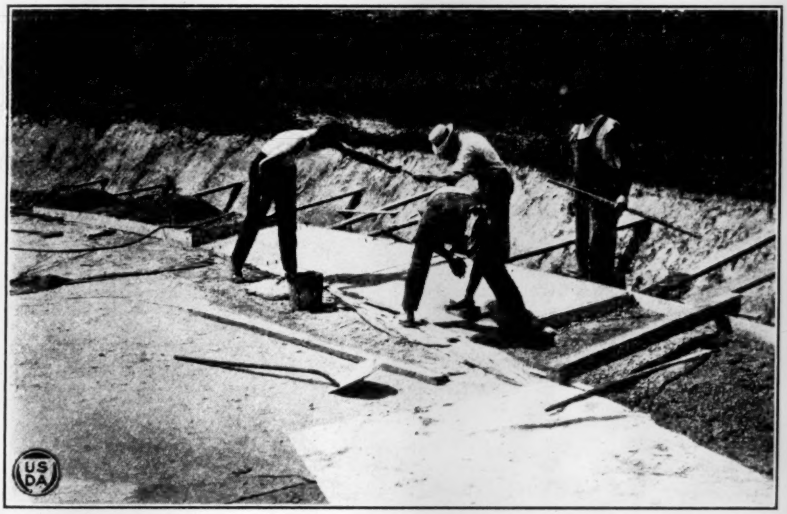

FIG. 2.—Construction View of Finishing of Concrete Pavement.

The test aggregates were proportioned by loose volume, each batch consisting of one bag of cement, $1\frac{1}{2}$ cu. ft. of sand, and 3 cu. ft. of coarse aggregate, except on those sections where other proportions were tried for experimental purposes. The concrete was mixed in a one-bag, power-driven batch mixer; and every effort was made to have the consistency as nearly uniform as possible except in the group where it was varied designedly. In view of the widely varying characteristics of the materials it was found impossible to control this factor absolutely. The consistency of the concrete going into

TABLE I.—LAYOUT OF TEST SECTIONS.

GROUP I.—SECTIONS 1 TO 10, INCLUSIVE.

Factor Studied: Effect of quality of stone as coarse aggregate.
Fine Aggregate: Potomac River sand.
Coarse Aggregate: Various. See Table II.
Proportions: 1:1½:3 by volume.

GROUP II.—SECTIONS 11 TO 19, INCLUSIVE.

Factor Studied: Effect of quality of gravel as coarse aggregate.
Fine Aggregate: Potomac River sand.
Coarse Aggregate: Various. See Table II.
Proportion: 1:1½:3 by volume.

GROUP III.—SECTIONS 35 TO 42, INCLUSIVE.

Factors Studied: Effect of grading and quality of slag as fine and coarse aggregate.
Fine Aggregate: Potomac River and slag sand. See Table III.
Coarse Aggregate: Various. See Table II.
Proportions: 1:1½:3 by volume.

GROUP IV.—SECTIONS 20 TO 26, INCLUSIVE, AND SECTION 50.

Factors Studied: Effect of grading and quality of sand as fine aggregate.
Fine Aggregate: Various. See Table III.
Coarse Aggregate: Dolomite. See Table II.
Proportions: 1:1½:3 by volume.

GROUP V*a*.—SECTIONS 27 TO 34, INCLUSIVE, AND SECTION 46.

Factors Studied: Effect of consistency, time of mixing and cement content.
Fine Aggregate: Potomac River sand.
Coarse Aggregate:
  Sections 27–34: Dolomite.
  Section 46: Potomac River gravel.

Proportions: 1:1½:3 unless otherwise noted.

Consistency:
  Section 27: Very dry.
  Section 28: Medium.
  Section 29: Wet.

Time of Mixing:
  Section 30: ½ minute.
  Section 31: 2 minutes.

Proportions:
  Section 32: 1:2:4 by volume.
  Section 33: 1:2:3 by volume.
  Section 34: 1:2½:5 by volume.
  Section 46: 1:2½:5 by volume.

TABLE I.—(*continued*)

GROUP V*b*.—SECTIONS 47 TO 54, INCLUSIVE.

Factor Studied: Effect of tolerance material in aggregates and one-size stone.
Fine Aggregate: Potomac River sand. See Table III.
Coarse Aggregate: Dolomite graded 1½ to ¼ in. unless otherwise noted.

Proportions:
Sections 47–53: 1:1½:3.
Section 54: 1:1.7:3.2.

Notes on Aggregates:
Section 47: Fine aggregate contains 15 per cent ¼–½-in. gravel.
Section 48: Coarse aggregate contains 15 per cent stone screenings.
Section 49: Fine aggregate contains 15 per cent ¼-½-in. gravel; coarse aggregate contains 15 per cent stone screenings.
Section 50: Fine aggregate, fine Potomac River sand. See Table II.
Section 51: Coarse aggregate, ¼–¾-in. only.
Section 52: Coarse aggregate, ¾-1½-in. only.
Section 53: Fine aggregate, fine Potomac River sand; coarse aggregate, ¾–1½-in. only.
Section 54: Aggregates as in Section 53. Proportions: 1:1.7:3.2.

GROUP V*c*.—SECTIONS 56 TO 62, INCLUSIVE.

Factors Studied: Effect of mortar top, hydrated lime and stone screenings.
Fine Aggregate: See Table III.
Coarse Aggregate: See Table II.
Proportions: 1:1½:3 unless otherwise noted.

Notes:
Section 56: Mortar top 1:1½ by volume.
Section 57: Mortar top 1:3 by volume.
Section 58: 12 per cent hydrated lime by volume added, based on weight of cement.
Section 59: 12 per cent hydrated lime by volume added, based on weight of cement.
Section 60: 12 per cent hydrated lime by volume added, based on weight of cement.
Section 61: Limestone screenings free from dust used in place of sand.
Section 62: Limestone screenings containing dust of fracture used in place of sand.

GROUP V*d*.—SECTIONS 43 TO 45, INCLUSIVE.

Factors Studied: Effect of mine chats and burnt clay as aggregates.
Fine Aggregate: See Table III.
Coarse Aggregate: See Table II.

Proportions:
Section 43: 1:1½:3.
Section 44: 1:1:3.
Section 45: 1:2:2.

NOTE.—Section 55 is not included in this report because an error was made in proportioning the materials.

TABLE II.—TESTS OF COARSE AGGREGATES.

Section No.	Type of Material	Source	Wear, per cent	Hardness	Toughness	Weight per cu. ft.		Absorption, per cent	Grading
						Solid	Crushed		
1	Argillaceous dolomite	Berkeley Co., W. Va	4.0	17.0	9	176	..	0.15	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
2	Altered diabase	Somerset Co., N. J	2.3	18.0	31	183	..	0.03	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
3	Quartzite	Minnehaha Co., S. D	1.8	18.7	22	165	..	0.14	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
4	Granite porphyry	Llano Co., Tex	2.4	18.7	20	164	..	0.15	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
5	Calcareous slate	Texas	4.0	18.3	22	163	..	0.51	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
6	Sandstone	Pine Co., Minn	13.8	14.8	4	156	..	1.23	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
7	Sandstone	Wise Co., Va	5.3	16.3	11	156	..	1.55	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
8	Argillaceous limestone	Huron Co., Ohio	6.3	10.3	5	157	..	3.70	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
9	Limestone	Presque Isle Co., Mich	9.5	13.3	5	162	..	0.80	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
10	Dolomite	Jones Co., Iowa	14.5	0.0	4	132	..	8.96	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
11	Gravel consisting of rounded fragments of quartz, schist, and sandstone	Potomac River	11.0[a]	....	..	158	..	1.09	$\frac{1}{4}$ - 1 in.
12	Gravel consisting of rounded fragments of dolomite	Will Co., Ill	9.3[a]	....		161	..	1.63	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
13	Gravel consisting of rounded fragments of limestone, dolomite, chert and sandstone	Warren Co., Ind	9.4[a]	....	..	159	..	1.76	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
14	Gravel consisting of rounded fragments of quartz, sandstone, limestone and granite	St. Joseph Co., Ind	[b]	....	..	160		1.48	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
15	Gravel consisting of rounded fragments of quartz, rhyolite, andesite and sandstone	Marathon Co., Wis	[b]	....	..	164	..	1.49	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
16	Gravel consisting of rounded fragments of granite, quartz and diorite	Hampden Co., Mass	14.3[a]	....	..	149	..	0.48	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
17	Gravel consisting of rounded fragments of quartz	Richland Co., S. C	29.0[a]	....	..	144	..	0.33	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
18	Gravel consisting of rounded fragments of quartz, granite, sandstone, quartzite and gabbro	Vanderburg Co., Ind	[b]	....	..	150	..	2.11	$\frac{1}{4}$ - 1 in.
19	Gravel consisting of rounded fragments of granite, sandstone, shale and limestone	Hancock Co., Iowa	[b]	....	..	149	..	4.45	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
20–34	Argillaceous dolomite	Berkeley Co., W. Va	4.0	17.0	9	176	..	0.15	......
35	Blast furnace slag	Montgomery Co., Pa	15.9	....	..	...	75	....	$\frac{1}{4}$ - $2\frac{1}{2}$ in.
36	Blast furnace slag	Montgomery Co., Pa	15.9	....	..	...	75	....	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
37	Blast furnace slag	Montgomery Co., Pa	15.9	....	..	...	75	....	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
38	Blast furnace slag	Montgomery Co., Pa	15.9	....	..	...	75	....	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
39	Blast furnace slag	Morris Co., N. J	...	....	..	...	56	....	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
40	Copper slag	Polk Co., Tenn	4.1	18.0	14	220	105	0.58	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
41	Copper slag	Middlesex Co., N. J	...	....	..	...	110	....	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
42	Lead slag	Middlesex Co., N. J	...	....	..	...	110	....	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
43	Chert chips	Jasper Co., Mo	[b]	....	..	...	..	...	No. 10 - $\frac{1}{2}$ in
44	Chert chips	Jasper Co., Mo	[b]	....	..	...	..	....	No. 10 - $\frac{1}{2}$ in
45	Burnt clay	St. Louis Co., Mo	[b]	....	..	...	..	....	$\frac{1}{4}$ - $\frac{3}{4}$ in.
46	Gravel consisting of rounded fragments of quartz, schist and sandstone	Potomac River	11.0[a]	....	..	158	..	1.09	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
47–55	Argillaceous dolomite	Berkeley Co., W. Va	4.0	17.0	9	176	..	0.15	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
58	Altered diabase	Polk Co., Wis	[b]	18.3	32	185	..	0.01	$\frac{1}{4}$ - $1\frac{1}{2}$ in.
59–62	Argillaceous dolomite	Berkeley Co., W. Va	4.0	17.0	9	176	..	0.15	$\frac{1}{4}$ - $1\frac{1}{2}$ in.

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[a] Test made in accordance with Method No. 2, Abrasion test for gravel, U. S. D. A. *Bulletin No. 949*, p. 3.
[b] Pieces not large enough for this test.

each section was measured by means of the slump test and flow table. The average results of the consistency tests are given for each section in Table IV. The concrete in practically all cases was of medium consistency and rather inclined to be too dry than too wet. All the coarse aggregates, unless otherwise noted, were graded from 1½ in. uniformly down to ¼ in. in size. Potomac river concrete sand, used as the standard fine aggregate, was well graded and of known quality. The concrete in each section was struck off by means of a wooden strike board and was finished with a wooden hand float.

TABLE III—TESTS OF FINE AGGREGATES.

Section No.	Type of Material	Source	Mechanical Analysis. Total per cent passing							Silt, per cent	Color, Plate No.	Tensile Strength Ratio	
			¼ in.	No. 10	No. 20	No. 30	No. 50	No. 100	No. 200			7 days	28 days
1–20	River sand	Potomac River	98	74	60	46	22	9	5	3.0	1	125	114
21	Bank sand	Merrimack Co., N. H.	94	66	35	15	3	1	1	0.5	1	71	70
22	River sand	Fayette Co., Pa	100	93	75	54	21	6	2	1.5	3–4	98	109
23	Bank sand	Marathon Co., Wis	99	86	66	34	7	1	1	0.4	1	127	123
24	River sand	Charleston Co., S. C.	100	98	83	53	20	3	1	..	1	92	92
25	River sand	St. Clair Co., Mich	100	68	55	47	18	2	1	0.5	1	145	126
26	River sand	Colorado River	100	89	55	16	2	1	1	0.4	1	126	108
27–37	River sand	Potomac River	98	74	60	46	22	9	5	3.0	1	125	114
38	Blast furnace slag sand	Montgomery Co., Pa	94	51	28	19	12	9	7	5.0	..	55	94
39	River sand	Potomac River	98	74	60	46	22	9	5	3.0	1	125	114
40	Copper slag sand	Polk Co., Tenn	99	85	47	17	6	3	2	1.0	..	96	132
41–42	River sand	Potomac River	98	74	60	46	22	9	5	3.0	1	125	114
43	"Rolled chat sand"	Jasper Co., Mo	100	58	33	22	15	11	9	5.4	..	200	199
44	"Jig sand"	Jasper Co., Mo	100	100	94	60	28	12	5	1.4	..	82	95
45	Burnt clay	St. Louis Co., Mo	99	76	51	33	19	12	8	3.8	..	108	127
46	River sand	Potomac River	98	74	60	46	22	9	5	3.0	1	125	114
47	River sand	Potomac River	83	63	51	39	19	8	4	3.0	1	...	...
48	River sand	Potomac River	98	74	60	46	22	9	5	3.0	1	125	114
49	River sand	Potomac River	83	63	51	39	19	8	4	3.0	1	...	...
50	River sand	Potomac River	100	99	91	65	19	5	2	1.2	1	90	84
51–52	River sand	Potomac River	98	74	60	46	72	9	5	3.0	1	125	114
53–54	River sand	Potomac River	100	99	91	65	19	5	2	1.2	1	90	84
55	Limestone screenings	Berkeley Co., W. Va	95	50	5	0	0	0	0		..	...	...
56–59	River sand	Potomac River	98	74	60	46	22	9	5	3.0	1	125	114
60	River sand	Potomac River	100	99	91	65	19	5	2	1.2	1	90	84
61	Limestone screenings	Berkeley Co., W. Va	95	58	30	16	8	4	2	...	..	...	..
62	Limestone screenings	Berkeley Co., W. Va	94	69	47	35	28	22	18	...	..	202	162

As the testing machine was expected to operate at a speed of approximately 20 miles per hour around a circle with a 100-ft. radius, a superelevation of about 7 in. was found necessary. This was not as much as was theoretically desirable, but it was found impracticable to properly finish the concrete surface on any greater slope. Iron bolts were cast in the pavement at regular intervals for the purpose of holding the rails which were to guide the testing machine. The rails were laid 42 in. center to center. A construction view of the test sections is shown in Fig. 2.

SECTIONS ARRANGED IN FIVE GROUPS FOR STUDY OF VARIOUS CHARACTERISTICS

The sections were divided for purposes of study into five major groups, as shown in Table I. The source, character, and physical characteristics of the various coarse aggregates are given in Table II and the corresponding information for the fine aggregate in Table III. The sections in group I were constructed with the purpose of studying the effect of variations in quality of crushed stone as coarse aggregate. Ten samples of stone varying in quality from hard, tough traps to very soft limestones were used for this purpose. In group II the effect of variations in the quality of gravel as a coarse aggregate was investigated, and for this purpose nine samples of gravel from various parts of the country were obtained. Group III comprised eight sections and was for the purpose of studying the behavior of slag as a concrete road aggregate. Both the size and quality of the slag as well as the effect of slag sand used as fine aggregate were studied. Four sections were constructed with blast-furnace slag, three of them using slag weighing approximately 75 lb. per cu. ft. and one in which the slag weighed 56 lb. per cu. ft. Copper and lead-smelter slags were used in the other three sections in this group. Group IV was composed of eight sections in which the type of sand was the object of study. The sands used ranged from a very coarse glacial sand from Wisconsin

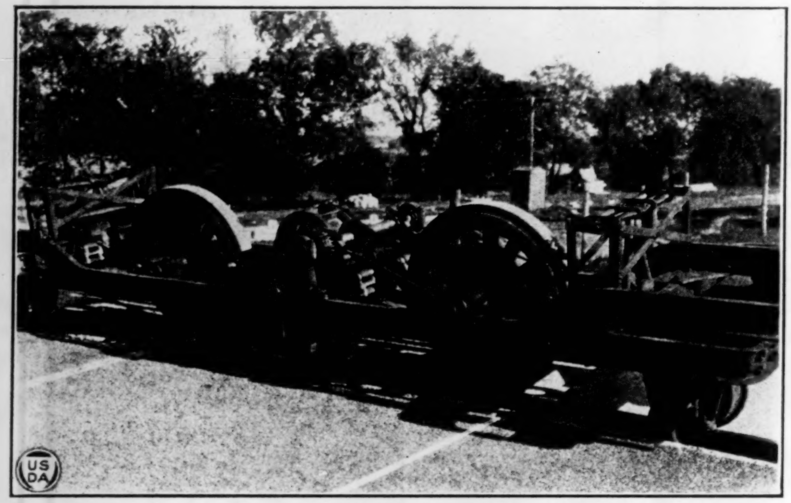

FIG. 3.—View of Testing Machine.

to a fine, pure quartz sand from South Carolina. Strength ratios varied from 126 to 70 per cent and the fineness moduli from 2.2 to 3.5. The sections in group V were constructed with the idea of noting the effect of various miscellaneous factors on the surface wear, such as consistency of the concrete, the time of mixing, proportions or cement content, grading of aggregates, and the effect of hydrated lime as an admixture. In addition, sections were constructed using mine chats from Joplin, Mo., and burnt clay as coarse aggregates and limestone screenings in place of sand as fine aggregate. Finally, two sections were built without coarse aggregate one in the proportion of 1 : 1½ and the other a 1 : 3 mortar.

DESCRIPTION OF THE TESTING MACHINE

A view of the testing machine is shown in Fig. 3. It was so constructed as to have approximately the same effect as ordinary truck traffic. Since the width of the test section was only 4 ft. the design of the machine included only one front and one rear truck wheel. The solid-rubber-tired wheels were mounted in a frame between two truck springs which served to carry the necessary loading of 600 lb. per inch of tire width on each of the truck wheels, the total load on each wheel being 3000 lb. The rear wheel was driven by means of an electric motor. The frame which carried the truck wheels and their loading was mounted in a flexible manner within another frame. The outer frame, equipped with four flanged car wheels, was supported and guided by railroad rails at each side of the test sections, and in turn guided the inner frame and truck wheels. The whole apparatus was propelled by the truck wheels which acted freely with their whole weight on the concrete surface. Two complete machines were constructed and coupled together in the test, with each of the truck wheels so aligned that all followed in the same path, approximately 6 in. in width. The abrasive action, thus concentrated upon a narrow path, was greatly accelerated. The machines were operated and controlled through a third rail system and were run at a speed of from 20 to 22 miles per hour.

TESTS OF CONTROL SPECIMENS

For each section of the pavement, with the exception of section 46, control specimens were made for the purpose of determining the strength of the concrete in compression, cross-bending, and resistance to wear. This group of specimens consisted of three 6 by 12-in.

cylinders, two 6 by 8 by 48-in. beams and three 8 by 8 by 5-in. Talbot-Jones wear blocks. A small amount of concrete was taken from each batch for the purpose of fabricating the control specimens, so that the concrete in these specimens may be considered to be fully representative of that in the test sections proper. Twenty-four hours after molding, the forms were removed and the specimens placed on the section which they represented. An earth covering was then placed over the entire section and kept continuously wet for 14 days, after which the concrete was exposed to the weather. All of the specimens were in an air-dry condition when tested at the age of 90 days.

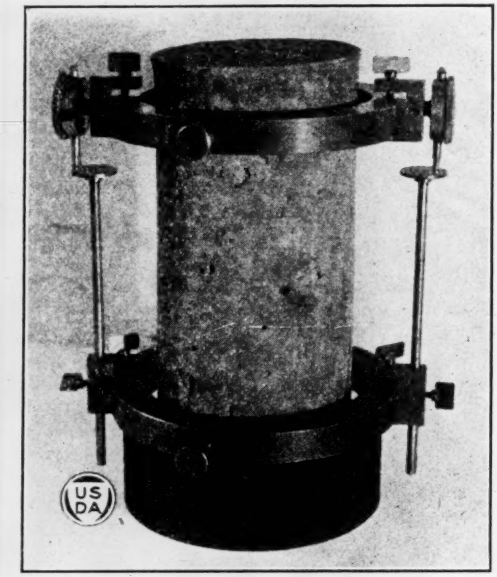

FIG. 4.—View of 2-Ring, 2-Dial Compressometer, Mounted.

Compression tests were made in a 200,000-lb. universal testing machine, following in detail the standard American Society for Testing Materials procedure. Deformation readings for determining the modulus of elasticity in compression were taken on two cyclinders from each section by means of an approved form of compressometer. This compressometer was of the two-ring, two-dial type and proved very sensitive, movements of the dials taking place under initial loadings of 40 lb. per sq. in. It is shown mounted on a specimen in

TABLE IV.—RESULTS OF CONTROL TESTS OF CONCRETE.

Section No.	Average Consistency[1]		Weight, lb. per cu. ft.	Compression Tests.[2] Age 90 Days		Transverse Tests.[3] Age 90 Days		Talbot-Jones Wear Tests.[4] Age 90 Days	
	Slump Test, in.	Flow Table		Crushing Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	Modulus of Rupture, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	Loss in Weight, per cent	Depth of Wear, in.
1	3	165	154	4 668	5 100 000	480	4 735 000	3.48	0.174
2	3	165	165	3 932	5 000 000	512	4 050 000	7.55	0.378
3	2	155	156	4 139	4 900 000	677	3 265 000	7.57	0.393
4	3	160	159	5 510	4 600 000	607	3 845 000	5.76	0.288
5	3	165	156	4 930	4 800 000	483	4 000 000	3.91	0.195
6	2	140	148	6 143	3 550 000	632	3 335 000	5.42	0.271
7	2	160	149	5 015	1 650 000	499	1 992 500	4.06	0.203
8	1	135	153	4 786	4 000 000	692	3 550 000	5.60	0.280
9	2	150	155	4 883	4 100 000	509	3 860 000	6.51	0.326
10	1	140	151	4 878	3 450 000	599	3 665 000	6.73	0.335
11	3	170	155	4 163	3 300 000	527	3 265 000	7.73	0.367
12	3	170	154	4 345	4 250 000	659	4 410 000	6.71	0.334
13	2	145	155	4 770	4 300 000	517	4 525 000	5.82	0.291
14	1	140	156	4 192	4 000 000	538	3 590 000	6.16	0.308
15	2	155	159	5 263	4 400 000	536	4 085 000	6.05	0.319
16	2	155	180	4 683	3 200 000	532	2 652 500	4.98	0.246
17	2	155	155	3 627	2 750 000	544	2 990 000	5.05	0.253
18	2	150	152	4 537	5 100 000	524	4 282 500	5.97	0.299
19	2	150	152	3 460	3 350 000	529	2 960 000	6.39	0.320
20	3	170	158	3 902	5 150 000	601	4 310 000	6.52	0.327
21	2	150	161	4 240	5 250 000	758	4 765 000	6.31	0.315
22	2	160	156	3 615	4 800 000	674	4 870 000	6.93	0.347
23	2	150	159	4 923	7 000 000	705	5 520 000	6.00	0.200
24	2	155	160	4 928	5 500 000	794	5 320 000	4.68	0.234
25	0	120	163	5 197	5 700 000	728	5 725 000	5.72	0.289
26	1	145	160	5 585	6 200 000	762	5 445 000	5.52	0.276
27	1	120	158	4 530	6 250 000	810	4 995 000	7.08	0.364
28	3	160	158	4 646	5 550 000	670	4 345 000	5.69	0.285
29	5	180	158	4 268	5 100 000	590	4 270 000	6.28	0.314
30	2	150	161	3 842	4 800 000	599	4 265 000	7.15	0.350
31	3	165	159	3 992	5 100 000	653	4 505 000	5.28	0.264
32	1	135	158	3 580	6 100 000	592	4 225 000	6.42	0.321
33	4	180	155	3 792	5 100 000	728	4 395 000	5.25	0.261
34	1	140	158	3 387	4 700 000	545	5 030 000	7.50	0.375
35	2	175	152	4 827	4 450 000	589	4 390 000	5.23	0.262
36	4	170	149	4 987	5 000 000	699	4 545 000	5.48	0.274
37	3	150	149	4 772	4 600 000	597	4 030 000	4.29	0.215
38	2	150	142	4 827	3 950 000	774	3 600 000	4.00	0.200
39	2	150	135	4 333	4 350 000	729	3 525 000	5.73	0.287
40	3	160	193	6 697	6 200 000	754	5 330 000	3.46	0.173
41	2	145	197	6 003	6 300 000	573	4 365 000	3.42	0.171
42	2	150	180	6 328	3 450 000	558	3 255 000	4.16	0.208
43	4	150	143	4 170	4 000 000	627	4 005 000	7.26	0.363
44	1	130	140	3 735	4 300 000	692	3 985 000	8.29	0.415
45	4	175	116	5 165	2 300 000	416	2 045 000	6.95	0.347
46	..	...	...	....	....	...	....	....	.....
47	2	155	156	4 290	5 000 000	623	4 230 000	5.50	0.276
48	1	120	159	5 363	5 100 000	762	4 585 000	4.92	0.246
49	1	135	159	4 597	4 960 000	788	4 642 500	7.06	0.363
50	2	155	158	4 988	5 250 000	668	4 427 500	5.63	0.282
51	1	135	162	4 852	5 150 000	742	5 005 000	6.11	0.305
52	2	150	163	5 263	6 150 000	635	4 515 000	5.38	0.269
53	4	165	160	5 372	5 380 000	706	4 205 000	5.78	0.289
54	2	155	156	5 100	4 670 000	620	4 195 000	5.90	0.295
55	..	...	...	....	....	...	....	....	.....
56	2	165	143	7 083	3 800 000	727	3 285 000	5.88	0.294
57	1	145	140	3 687	3 100 000	641	2 787 500	8.14	0.407
58	1	130	165	5 533	6 200 000	667	4 805 000	4.96	0.248
59	3	150	160	4 205	5 300 000	749	4 187 500	6.78	0.286
60	3	155	154	4 630	5 430 000	652	4 780 000	5.41	0.271
61	1	135	152	3 635	4 550 000	568	3 945 000	6.78	0.339
62	3	150	158	3 675	4 500 000	656	4 125 000	6.85	0.343

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[1] Each result is the average of four tests. The slump test was made with the 4 by 8 by 12-in. truncated cone. The flow test was made with the 30-in. flow table, using 15 drops from a height of $\frac{1}{2}$ in. The flow equals the final diameter of a truncated cone of wet concrete whose original diameter was 100.

[2] Each result is the average of tests of three 6 by 12-in. cylinders.

[3] Each result is the average of two tests on beams 6 in. wide, 8 in. deep, and 48 in. long, tested on a 42-in. span.

[4] Each result is the average of three 8 by 8 by 5-in. wear blocks.

Fig. 4. The results of the compression tests, including modulus of elasticity in compression, are given in Table IV.

The transverse tests were made on 6 by 8 by 48-in. beams, using a span of 42 in. with center loading. The beams were supported at the ends by specially designed rockers having uniform bearing against the bottom surfaces of the beams and a rocker adjustment upon the supporting plates. These plates were in turn fastened to the flanges of the I-beams at such distance that the centers of the supporting rockers were 42 in. apart, center to center. The deflection measuring device consisted essentially of three U-shaped brackets of strap iron fastened at the neutral axis on each side of the beam with pointed set screws. Two of the brackets were placed directly over the end supports and the third fastened at the center of the span. This center bracket supported two 0.001-in. Ames dials, one on each side of the beam. Supported horizontally by the set screws of the end brackets were two wooden bars, one on each side of the beam, against which the plungers of the Ames dials rested. Fig. 5 shows the details of this deflection measuring apparatus. The loads were applied through a $\frac{3}{4}$-in. ball resting on a $\frac{1}{4}$-in. steel bar about 7 in. long. They were applied very slowly in increments of 500 lb. until failure occurred. Between the 2500-lb. load and failure the dials were watched very closely to catch the maximum deflection at the point of rupture. Table IV gives the results of the tests for modulus of rupture and modulus of elasticity in bending for the beams of the 62 test sections.

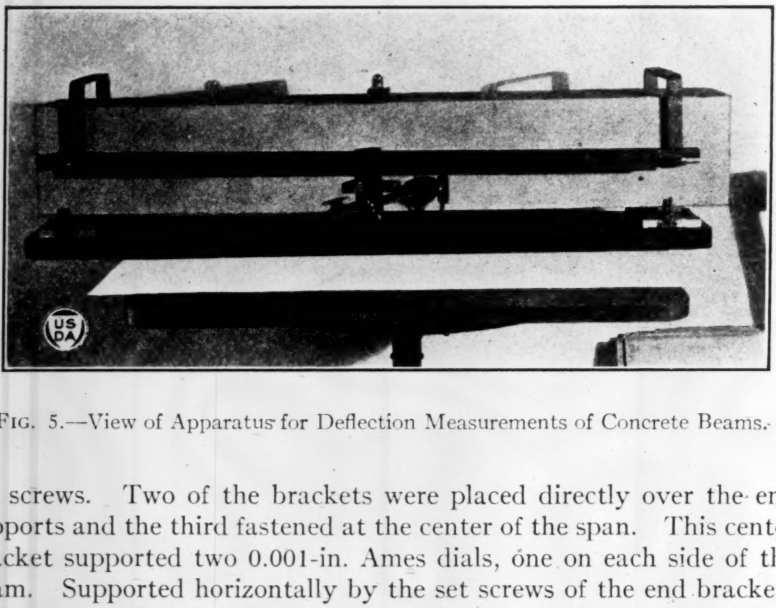

FIG. 5.—View of Apparatus for Deflection Measurements of Concrete Beams.

The laboratory wear tests were made in accordance with the methods employed by Abrams[1] using the Talbot-Jones rattler and the results are also given in Table IV.

TESTS OF THE CIRCULAR PAVEMENT

Operation of the testing machine was begun in March, 1925, about six months after the completion of the test sections. As already noted, the tests have so far been run in two stages, the first consisting of 75,000 trips of the machine equipped with solid rubber tires, and the second of 25,000 trips of the same machine with the front wheel of each truck equipped with non-skid chains. Ordinary pneumatic automobile tire chains, with 18 cross chains to the tire, were used in these experiments. The test with tire chains was started in July, 1923, and was continued intermittently until February, 1924, the wheels following an entirely different path from that followed during the first stage. Although a considerable portion of the second stage was run during December and January, weather conditions were so favorable that practically no snow or ice was encountered.

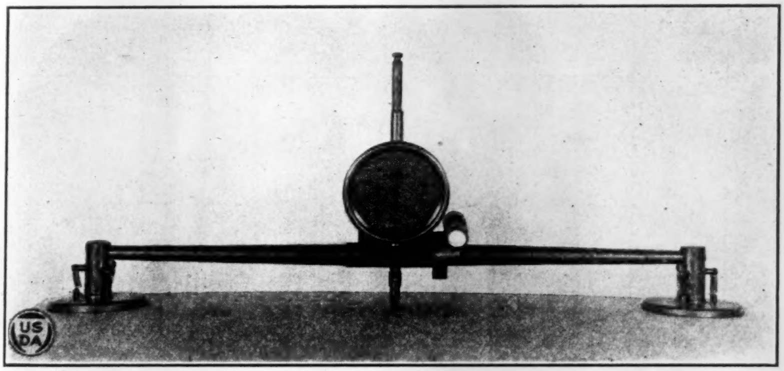

FIG. 6.—View of Instrument for Measuring Wear on Concrete.

For the purpose of determining the actual amount of wear which took place under both the rubber-tire and chain traffic, measurements were taken at four places on each test section by means of the special device shown in Fig. 6. This device consists essentially of a rigid bar about 11 in. in length mounted on two flat circular plates which rest upon the pavement and which are pivoted to the cross-bar through universal joints. An Ames dial with a plunger capable of 1-in. extension is mounted rigidly at the center of the cross-bar together with a cross-bubble for leveling the apparatus. Measurements were taken at certain points on the section, the locations of which were fixed by black circular spots of the same diameter as the bearing plates. With the instrument placed exactly on these spots, which were of course outside the line of travel, differences of reading on the dial between any two successive measurements represented the actual amount of wear which had taken place during the interval. An average of four readings on a section taken by this method is probably a fair indication of the wear on the section as long as it remains fairly uniform. Development of marked inequalities in wear, however, made this method very uncertain, so that for the final measurement under chain traffic another scheme was used. This consisted in taking a plaster cast of a portion of each section about 12 in. long, and somewhat wider than the width of the traffic groove. An average 12-in. length of each section was selected for this purpose. The casts were then sawed longitudinally through the center so that an exact profile of the surface of the pavement was obtained Photographs were

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[1] D. A. Abrams, "Wear Tests of Concrete," *Proceedings*, Am. Soc. Testing Mats., Vol. 21, p. 1013 (1921).

TABLE V.—AVERAGE DEPTH OF WEAR UNDER RUBBER TIRE AND CHAIN TRAFFIC

Section No.	Depth of Wear, in.		Section No.	Depth of Wear, in.		Section No.	Depth of Wear, in	
	Solid Rubber Tires, 55,000 Runs	Tires Equipped with Chains, 25,000 Runs		Solid Rubber Tires, 55,000 Runs	Tires Equipped with Chains, 25,000 Runs		Solid Rubber Tires, 55,000 Runs	Tires Equipped with Chains, 25,000 Runs
1	0.018	0.37	21	0.016	0.32	41	0.014	0.18
2	0.006	0.30	22	0.011	0.43	42	0.013	0.23
3	0.012	0.27	23	0.013	0.31	43	0.010	0.99
4	0.008	0.27	24	0.005	0.30	44	0.006	0.61
5	0.005	0.22	25	0.009	0.31	45	0.014	0.55
6	0.010	0.58	26	0.008	0.30	46	0.012	0.35
7	0.007	0.42	27	0.012	0.46	47	0.013	0.35
8	0.006	0.52	28	0.008	0.31	48	0.015	0.35
9	0.012	0.78	29	0.006	0.40	49	0.014	0.38
10	0.013	0.87	30	0.011	0.38	50	0.009	0.38
11	0.010	0.24	31	0.012	0.28	51	0.011	0.35
12	0.013	0.35	32	0.015	0.25	52	0.005	0.23
13	0.008	0.38	33	0.005	0.25	53	0.004	0.37
14	0.009	0.35	34	0.010	0.46	54	0.011	0.34
15	0.008	0.24	35	0.009	0.43	55	.....	....
16	0.008	0.30	36	0.012	0.40	56	0.009	0.33
17	0.007	0.33	37	0.007	0.27	57	0.009	0.89
18	0.012	0.18	38	0.014	0.57	58	0.012	0.26
19	0.009	0.40	39	0.005	0.89	59	0.006	0.30
20	0.008	0.21	40	0.008	0.27	60	0.014	0.30
						61	0.007	0.44
						62	.....	0.41

then made of these longitudinal sections. By blocking out everything except the area included between the horizontal line representing the original surface of the pavement and the final profile, an exact record of both the amount and character of wear was secured. The average depth of wear in inches over this 12-in. section was readily calculated by dividing the area by the length of the section.

As already noted, measurements were taken with the Ames dial to determine the amount of wear taking place under the rubber-tired traffic. Table V give the measurements of depth in inches for each of the 62 test sections at the end of 55,000 trips of the testing machine (equivalent to 220,000 passages of one wheel). It will be noted that surface wear under these conditions is practically negligible, amounting at the point of maximum depth to only 0.018 in. In fact a slight discoloration of the surface is about the only visible evidence of the traffic which has passed over it. This was true of every test section regardless of the quality of the aggregates composing the concrete. As a matter of fact, the various coarse aggregates did not come under test at all due to the fact that they were protected by the thin mortar top which formed the finished surface of each section. These observations lead to the conclusion that rubber-tired traffic, without impact, produces no actual wear on the surface of a concrete pavement, at least as long as the protecting mortar top remains intact. It must be remembered, however, that traffic on our highways is not confined entirely to vehicles with rubber tires. There is still a certain percentage of steel-tired traffic, as well as an appreciable amount of traffic using non-skid chains, especially in the Northern states during the winter months. Moreover, the solid rubber tires used in these experiments were new and therefore produced no impact or abrasion such as might result from the use of badly worn or broken tires, where the rim comes in contact with the pavement.

SIGNIFICANCE OF THE CHAIN TRAFFIC TESTS

It is realized, of course, that chain traffic on concrete highways is not dense enough, except in isolated instances, to cause any such wear of the surface of a pavement as was produced on the test sections. Wear, however, does take place at the unprotected edges of joints and cracks, eventually causing raveling or disintegration unless carefully maintained by the use of bituminous materials. It was believed that the relative resistance offered by the various sections to the chain traffic would be a fairly reliable index of the ability of the several materials to resist the combined destructive influences of traffic, whether such

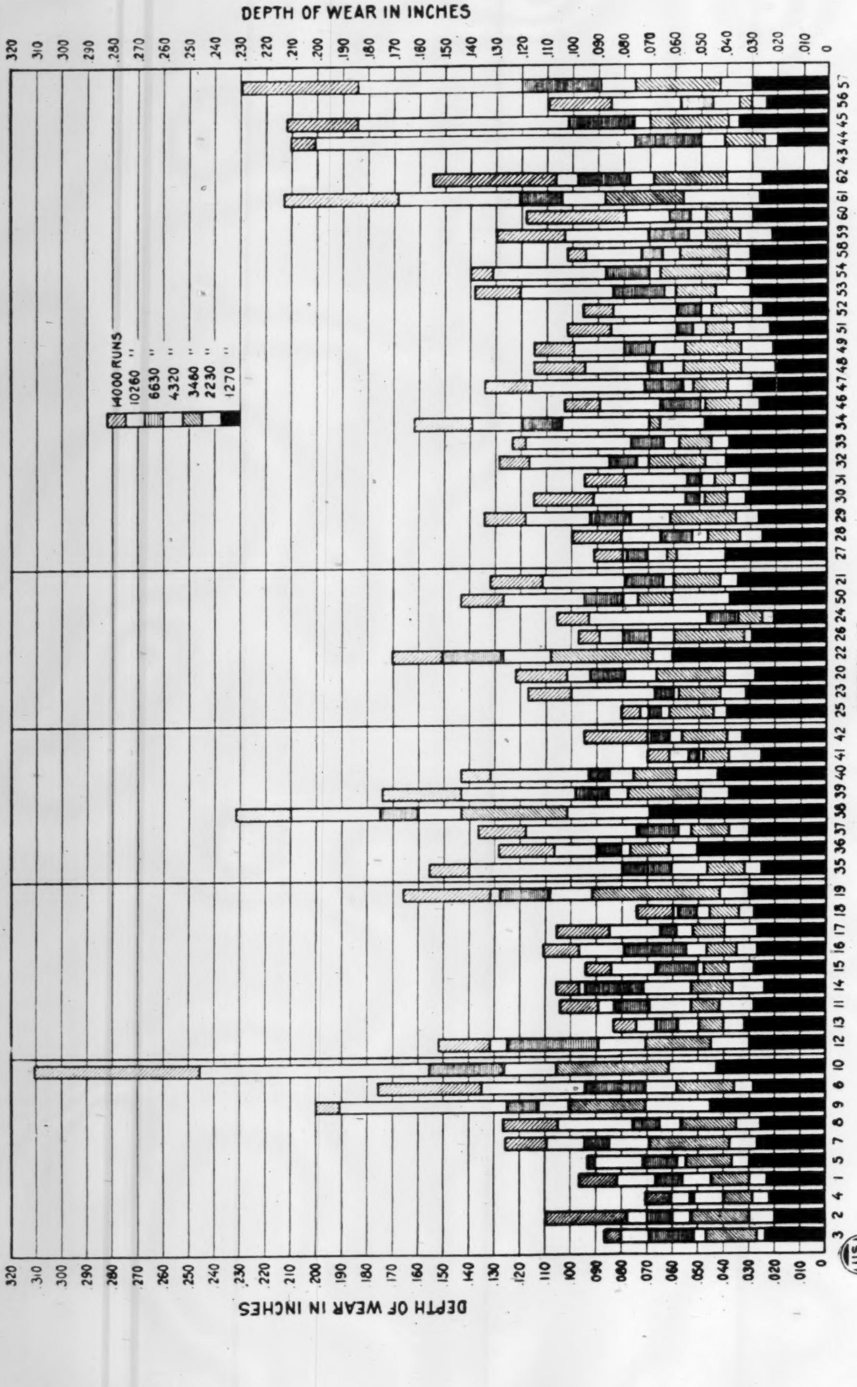
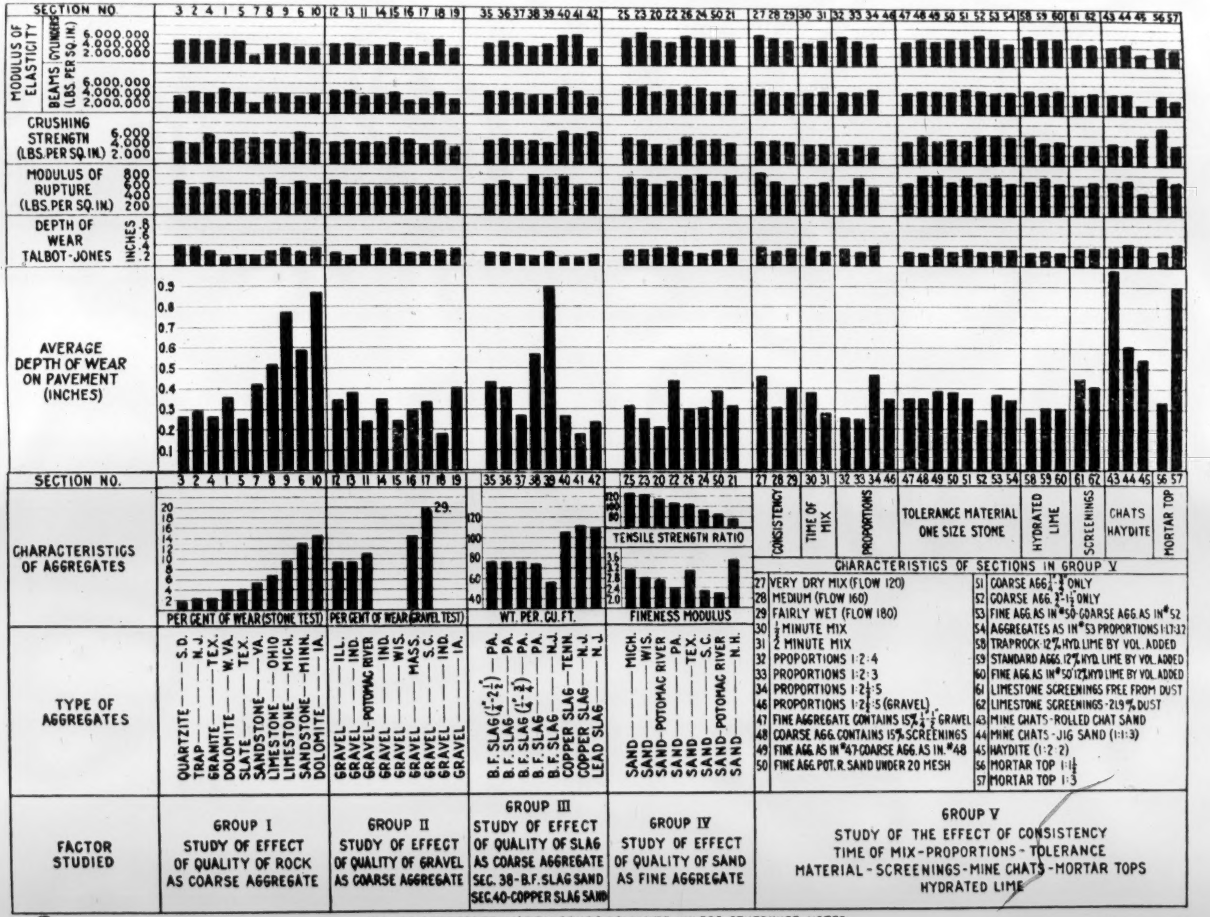


FIG. 7.—Readings of Depth of Wear at Various Periods during Test with Chains.

The data for section 43 are not available.



COARSE AGGREGATE, MARTINSBURG DOLOMITE UNLESS OTHERWISE NOTED
FINE AGGREGATE, POTOMAC RIVER SAND UNLESS OTHERWISE NOTED

FIG. 8.—Wear Caused by Non-Skid Chains, with Tests of Aggregates and Control Tests of Concrete.

influences produce wear at joints or cracks or cause surface disintegration. Taking the above facts into consideration, it was felt that the question was not definitely answered by simply determining that rubber tires rolling over the pavement produce no wear. It was decided therefore to continue the test, using the non-skid chains, this being not only the simplest but also the fairest method of securing the desired information.

The chains produced a noticeable effect on the surface from the beginning. Wear was rapid and progressive. Marked differences in the behavior of the different materials was also noted. In fact, at the completion of 25,000 runs, a groove almost one inch in depth had been cut in certain of the sections, whereas others showed as little as 0.2 in. wear—only about one-fifth as much. It will be of interest to take up the several groups as outlined in Table I and discuss the behavior of the several sections with respect to the kind and quality of materials used in their construction.

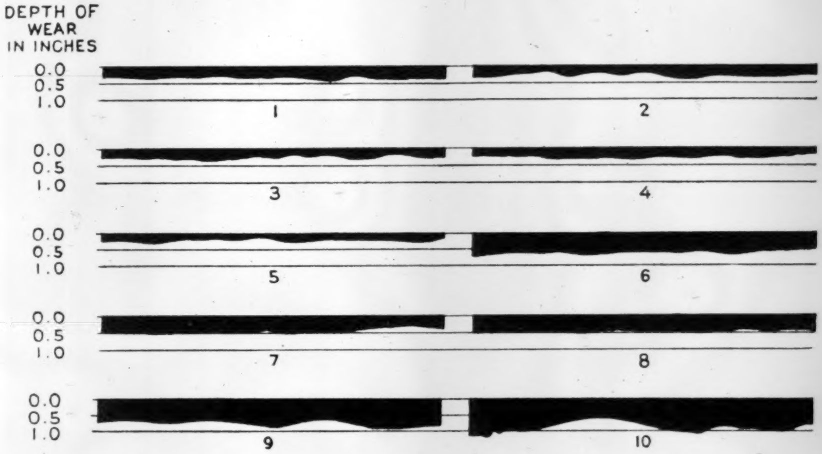
DISCUSSION OF WEAR CAUSED BY NON-SKID CHAINS

Ames dial readings taken at various times during the test with chains are plotted in Fig. 7. These results show the progress of wear from time to time. The first set of readings, for instance, was taken about the time the coarse aggregates became exposed so that it may be considered that only about 1000 runs of the machine with chains were necessary to wear away the thin mortar top which resisted without appreciable damage over 75,000 runs of the same machine without chains.

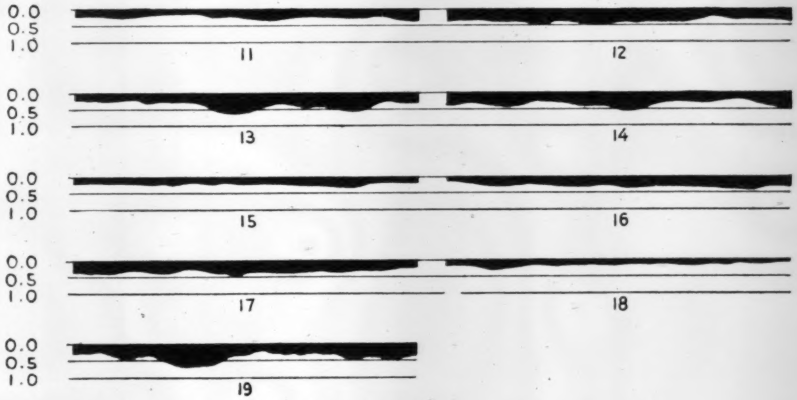
The depth of wear at the conclusion of the second stage, together with the results of tests of the aggregates and the control tests of the concrete, are plotted together for purposes of comparison in Fig. 8. The total depth of wear under chain traffic and the corresponding wear when the machine was operated without chains are also tabulated in Table V. For the purpose of studying the relative uniformity as well as depth of wear, reproductions of the plaster cast profiles are likewise given in Figs. 9, 10, 11 and 12. A discussion of the results of the wear tests, group by group, follows.

GROUP I (SECTIONS 1–10)—EFFECT OF QUALITY OF STONE

Reference to group I in Figs. 8 and 9 reveals some very interesting facts. In Fig. 8 the sections in group I are arranged in the order of the resistance to wear of the various aggregates, as measured by the standard Deval abrasion test. It will be observed that the wear on the sections containing the soft limestones and sandstones was much greater than on the sections in which the harder materials were used. Sections 6, 9 and 10 in particular, containing the poorest materials from the standpoint of the laboratory test, show excessive wear in the pavement. On the other hand, sections 1 to 5, inclusive, all of which contain aggregates having a percentage of wear of 4.0 or less, show much less surface wear.



Group I.—Effect of Quality of Stone as Coarse Aggregate.



Group II.—Effect of Quality of Gravel as Coarse Aggregate.

FIG. 9.—Reproduction of Plaster-Cast Profiles Showing Wear of Concrete Pavements under Chain Traffic.

An interesting point in connection with this group is the relation between the wear on the mortar matrix and the wear on the coarse aggregates. Reference to section 56, which is a 1 : $1\frac{1}{2}$ mortar top, shows a wear of 0.33 in., which is only a little greater than the wear on sections 2, 3 and 4 in which the hard and tough trap, quartzite, and granite were used. From the standpoint of surface wear it would seem, therefore, that it is only necessary that the coarse aggregate be at least as resistant to wear as the mortar matrix. Even a good mortar matrix, on the other hand, is apparently not able to protect a poor coarse aggregate once it has been exposed, as witness the behavior of sections 9 and 10. Both of these sections contained extremely soft limestones which have been proposed for use in concrete roads. The results of this test, however, would indicate that stone so soft that it will show in the laboratory a percentage of wear over 7 should not be used in the wearing course of concrete roads.

Another interesting point in connection with the first group is the behavior of the sandstone in section 6. This is the so-called Kettle River sandstone, which gave in the laboratory a percentage of wear of 13.0. Reference to Fig. 8 will show that the wear on section 6, although deep, was exceptionally uniform. The depth of wear also is not so great in proportion to the percentage of wear in the Deval test as in the case of the soft limestone sections. Whether this means that sandstones are better than limestones of equal hardness it is impossible to say, although as we shall see later certain sections in the gravel group show the same relative behavior. With regard to uniformity of wear, the moderately hard aggregates, that is, those of about the same resistance to abrasion as the mortar matrix, seem to have all the best of it. Reference to Fig. 8 and a visual examination of the sections themselves show that section 1 is somewhat smoother than either section 2, containing the trap, or section 3, containing the quartzite, and is much smoother than sections 9 and 10 in which the very soft limestones were used. There is not much choice between sections 1 and 4 or 5. Section 8, although worn rather deeply, is also smooth. This is an Ohio limestone with a percentage of wear of 6.0.

GROUP II (SECTIONS 11–19)—EFFECT OF QUALITY OF GRAVEL

In this group are nine sections in which various types of gravel were used. The most noticeable fact about this group is that although a very wide range in quality of gravel is represented, in no case was the depth of wear so great as in five of the sections in group I. When tested by the Rea[1] abrasion test, the gravel samples ranged from 9.3 to 29.0 per cent loss. Several of the samples consisted of pieces too small to make the abrasion test. Section 17 is a remarkable one. Although the South Carolina quartz gravel used in this section showed a percentage of wear of 29.0 (which is roughly equal to about 10.0 in the Deval abrasion test), the depth of wear is but little above the average for all the gravel sections and is not so great as in many of the stone sections. A close examination of this gravel shows that it is made up entirely of quartz pebbles of varying hardness, on the inside, but all protected by a hard exterior shell. A pebble when struck even a light blow will fly to bits, yet it is very difficult to scratch the surface with a knife. Apparently the quality of hardness was more important than toughness in resisting surface wear on these test sections, which leads to the conclusion that the modified Deval test for gravel may be too severe. Because of the presence of the large shot in the rattler, it is distinctly a test for toughness. The worst gravel from the standpoint of depth of wear is the one in section 19. This gravel contained about 5 per cent of shale particles and was submitted as an example of an aggregate of doubtful quality.

While the gravel sections appear to advantage in comparison with the stone sections from the standpoint of depth of wear, comparison as to uniformity of wear is not favorable to them. Sections 15 and 16, both containing glacial gravels, show up best in this respect. It is an interesting fact in this connection that the four sections (12, 13, 14 and 19) in which limestone is a constituent material of the gravel are the poorest as regards uniformity of wear. In sections 13 and 14, the gravels contain quite an appreciable amount of soft sandstone pebbles which have been worn away by the action of the chains, leaving marked depressions in the surface. The result is well illustrated in Fig. 9. On the other hand, the mere fact that the fragments are smooth and rounded appears to make little difference as far as wear is concerned. Section 18 is a good example. Before the chain traffic was well under way, the prediction was freely made that the smooth, rounded pebbles composing this sample would speedily kick out. As a matter of fact, this is one of the best of the gravel sections, especially as regards depth of wear.

Summing up, it would appear from these tests that gravel as a class should prove as satisfactory for aggregate in concrete as crushed stone, provided it is free from an excess of soft or disintegrated pebbles.

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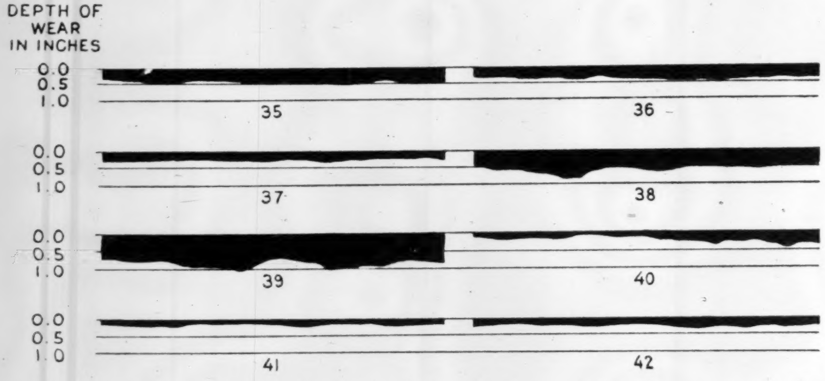
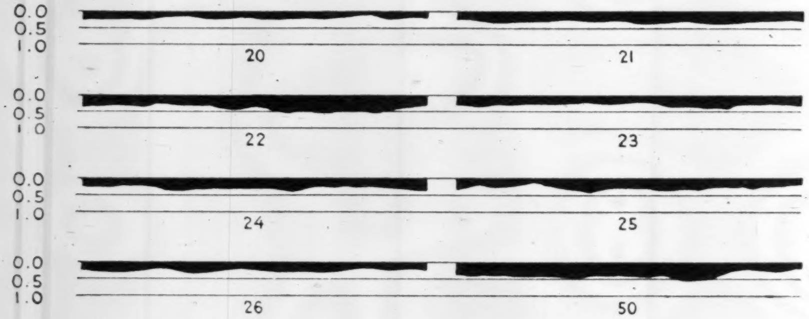
[1] U. S. Department of Agriculture *Bulletin No. 949*, p. 3.

GROUP III (SECTIONS 35–42)—EFFECT OF QUALITY OF SLAG

The sections in group III were arranged with the object of studying a number of factors which are involved in the selection of slag as concrete aggregate. In the first place it was of interest to determine the relative wear of slag concrete in which the maximum size of the coarse aggregate varied as follows: $2\frac{1}{2}$ in. in section 35, $1\frac{1}{2}$ in. in section 36, and $\frac{3}{4}$ in. in section 37. The weight per cubic foot, indicative of the quality of the slag, remained constant at 74 lb. per cu. ft. in these sections. In section 38 the same slag, graded $1\frac{1}{2}$ to $\frac{1}{4}$ in., but combined with slag sand in place of Potomac river sand, was used. Section 39, however, contained slag weighing only 56 lb.



Group III.—Effect of Quality of Slag as Coarse and Fine Aggregate.

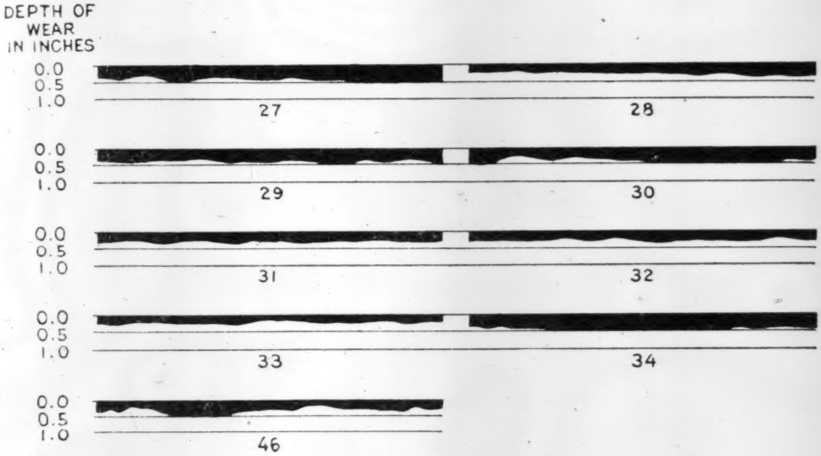


Group IV.—Effect of Quality of Sand as Fine Aggregate.

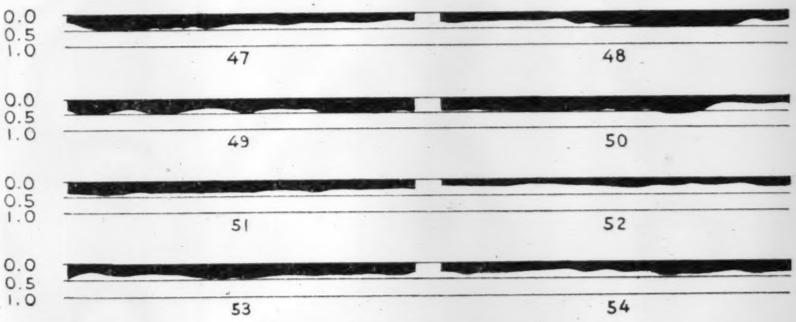
FIG. 10.—Reproduction of Plaster-Cast Profiles Showing Wear of Concrete Pavements under Chain Traffic.

per cu. ft. Copper and lead-smelter slag, with both Potomac river and copper slag sand were employed in the construction of sections 40 to 42, inclusive.

Comparing, first, sections 35 to 37, it is observed that considerably less wear has taken place on the section containing the $\frac{3}{4}$-in. maximum size. In fact, the total wear on this section was about the same as on the sections containing the best quality of stone and gravel, which is interesting in view of the impression that slag is not suitable for concrete road construction under any circumstances.



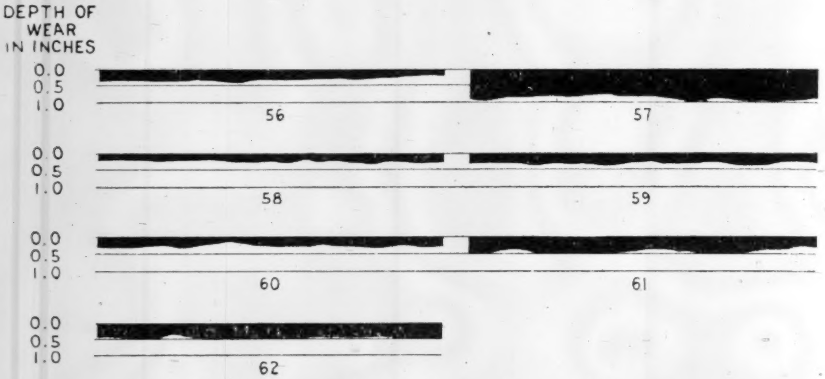
Group Va.—Effect of Consistency, Time of Mixing and Cement Content.



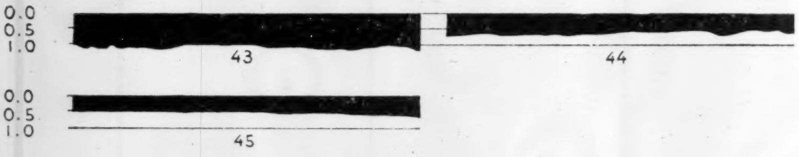
Group Vb.—Effect of Tolerance Material in Aggregates and One-Size Stone.

FIG. 11.—Reproduction of Plaster-Cast Profiles Showing Wear of Concrete Pavements under Chain Traffic.

Section 39, however, in which the 56-lb. slag was used, tells a different story, the wear being over three times as great as that on section 37. A comparison of the behavior of these sections illustrates very clearly the value of keeping the light and porous material in blast-furnace slag down to a minimum. In the light of these experiments, it would seem that the requirement of 70 lb. per cu. ft. used in a good many states is about correct. Blast-furnace-slag sand as a substitute for natural sand was tried as the fine aggregate in section 38. The results were not very encouraging, due probably to the fact that the extreme harshness of the concrete made it very difficult to finish properly. The total wear on this section was 0.57 in. or twice as great as on the corresponding section using Potomac River sand.



Group Vc.—Effect of Mortar Top, Hydrated Lime and Stone Screenings.



Group Vd.—Effect of Mine Chats and Burnt Clay as Aggregates.

Fig. 12.—Reproduction of Plaster-Cast Profiles Showing Wear of Concrete Pavements under Chain Traffic.

As might be expected, the copper and lead-smelter slag used in sections 40 to 42 showed very little wear. Section 41 showed less wear than any other of the 62 test sections. There would seem to be no reason why such materials as these should not make excellent aggregates for concrete roads so far as durability is concerned. Unfortunately, however, the great weight of smelter slags, involving high transportation costs, limits their use to a considerable extent.

In conclusion, it may be said that the slag experiments indicate:

1. That somewhat better results are secured by the use of the smaller sizes;
2. That the weight per cubic foot should be not less than 70 lb.;
3. That blast-furnace-slag sand does not make a satisfactory substitute for natural sand, and
4. That copper and lead-smelter slag form excellent aggregates so far as resistance to wear is concerned.

GROUP IV (SECTIONS 20–26 AND 50)—QUALITY OF SAND

In sections 20 to 26 and in section 50, variations in wear, due both to quality and grading of natural sand as fine aggregate, were studied. Sands were selected for this purpose varying in "tensile strength ratio" from 126 to 70 per cent of standard Ottawa sand and from 2.2 to 3.5 in fineness modulus. In Fig. 8 the sections are arranged in the order of decreasing tensile strength ratio. Of this group, section 22, in which a river sand from Fayette County, Pennsylvania, was used, developed the greatest depth of wear, a little over 0.4 in. This sand contained an appreciable amount of carbonaceous shale, which probably accounts for the increased wear. It was also a rather fine sand, only 25 per cent being retained on the No. 20 sieve. The next greatest wear took place on section 50, which contained the fine Potomac River sand. Reference to Table IV will show that only 9 per cent of this sand was coarser than a No. 20 sieve, and that the strength ratio at 28 days was only 84 per cent. Four of the test sections, 21, 24, 25 and 26, all showed about the same resistance to wear, about 0.3 in. With the exception of section 24, all of these may be classed as coarse sands, that is they contain more than 30 per cent of particles coarser than No. 20 sieve. The sand in section 24, which was from South Carolina, though considerably finer, with only 17 per cent retained on the No. 20 sieve, was of exceptionally good quality, being composed entirely of pure quartz grains. A comparison of this sand with that used in section 22 is of interest because they have approximately the same grading, indicating that the variation in wear is probably due to the difference in the quality of the material. Section 20, Potomac River sand, and section 23, containing a glacial sand from Marathon County, Wisconsin, showed the smallest amount of wear. Both of these would be classed as coarse concrete sands.

The tests in general indicate the value of the coarse particles in reducing wear. For example, compare sections 20 and 50, in which Potomac River sand was used. The materials in these sections were identical except that the sand in section 50 was finer, the proportion of particles retained on the No. 20 sieve being reduced from 40 to 9 per cent. The effect on wear is quite marked.

When we come to consider the bearing which the strength-ratio test has on the pavement wear, we have difficulty in establishing any relation. The wide range in briquette strength is not reflected in the resultant wear any more than in the concrete strength of the materials. Reference to Fig. 8 will illustrate this. This is probably due to the fact that the factors which influence the strength, that is, gradation and quality of sand grains, do not affect the surface wear to the same degree. For instance, the mortar strength test is made on a 1 : 3 mix and compared with an Ottawa sand mortar in the same proportion, whereas the cement-to-sand ratio in the test sections was $1:1\frac{1}{2}$. The discrepancy in results, in so far as this test is concerned, is most marked in the case of section 21, in which a glacial sand from New Hampshire containing quite an appreciable percentage of feldspar was used. A strength test of this sand developed only 70 per cent of the strength of Ottawa sand in spite of the fact that the sand was very coarsely graded. Although this section has worn somewhat more than the Potomac River sand sections, the difference is not nearly so great as might be supposed from the results of the mortar strength test. It would seem, therefore, that the strength-ratio test is of questionable value as an indication of the quality of sand for concrete pavement work, at least in so far as resistance to wear is concerned. Its bearing on concrete strength both in compression and cross-bending will be discussed later.

GROUP V*a* (SECTIONS 27–34 AND 46)—EFFECT OF CONSISTENCY, TIME OF MIXING AND CEMENT CONTENT

In group V*a*, three very important factors having a bearing on the quality of concrete were investigated. The effects of variation in consistency show up in a very interesting way. Section 28, which contained concrete of what might be termed average consistency, that is, slump about 3 in., showed considerably less wear than either section 27, which was a very dry concrete, slump about 1 in., or the very wet mix with a 5-in. slump used in section 29.

The concrete comprising section 30 was mixed only one-half minute to compare with section 31, on which a two-minute mix was tried. The wear is somewhat less for the longer period. Moreover, section 31 checks fairly closely with section 28, in which the time of mixing was one minute, indicating that not much is gained, from the standpoint of wear, by mixing more than one minute.

As to effect of cement content on wear, the tests seem to show that for the usual mixes employed in concrete road construction, that is, 1 : 1½ : 3, 1 : 2 : 3, and 1 : 2 : 4, the actual cement content has very little influence on wear. This is illustrated by comparing sections 28, 32, and 33. This conclusion is not surprising in view of the fact that cement in itself has very little resistance to abrasion but acts simply as a binder, so that for any mix in which the cement content is high enough to produce a strong bond, the actual wear will be proportional to the hardness of the aggregates. This further emphasizes the point brought out in the discussion of the coarse aggregates, to the effect that the destructive action producing wear does so more by abrasion than by impact, and that hardness rather than toughness is the essential property in the aggregate. When we come to section 34, however, we find a different condition. Here we have a 1 : 2½ : 5 mix, a cement-to-sand ratio of 1 : 2½. The wear on this section is much greater than on any other in this group, indicating that a 1 : 2 mortar is about as lean as should be used. The 1 : 2½ : 5 gravel section 46, although not showing as high an average depth of wear as section 34, wore very unevenly, verifying the indications from the tests in groups I and II with regard to the relative uniformity of wear shown by crushed stone *versus* gravel.

GROUP V*b* (SECTIONS 47–54)—EFFECT OF TOLERANCE MATERIAL AND ONE-SIZE STONE

There has been considerable controversy from time to time regarding the allowable limit for the so-called tolerance material in fine and coarse aggregates proposed for use in concrete pavements. Many specifications limit this amount of over or under-size material to not more than 5 per cent. The sections in this group were built for the purpose of noting the effect on surface wear of allowing a 15-per-cent tolerance, as well as the effect of one-size instead of graded stone. Section 47 is a nominal 1 : 1½ : 3 mix in which the sand carried 15 per cent of gravel passing a ½-in. and retained on a ¼-in. screen. In section 48, the stone contained 15 per cent of coarse limestone screenings while in section 49 both aggregates contained 15 per cent of tolerence material. The total wear is somewhat greater on all of these sections than on the corresponding sections, sections 1, 20 and

28, in which accurately screened aggregates were used. They are also somewhat rougher as may be noted by referring to Figs. 10 and 11. As would be expected, section 49 shows the greatest wear, amounting to 0.38 in. Sections 51 and 52 showed surprising results. Section 51 contained $\frac{1}{4}$ to $\frac{3}{4}$-in. stone only, while in section 52 only the $\frac{3}{4}$ to $1\frac{1}{2}$-in. sizes were used. The wear is noticeably less on section 52. Section 53 is the same as section 52, except that the fine Potomac River sand was used in place of the regular concrete sand. The wear is very much greater, illustrating again the marked effect of the coarser sand grains in preventing wear. Section 54 contains the same aggregates as section 53, in the proportion of 1 : 1.7 : 3.2. There is practically no difference in wear.

The tests in group V*b* in general indicate that variations in gradation of aggregates within the limits tried do not affect the wear to any great extent, other things being equal. It must be realized, however, that from the standpoint of uniformity in workability and consequently in strength, it is very important to have uniformly graded material in a concrete road job. A harsh-working mix caused by poorly graded aggregate almost invariably results in poor concrete in the field. If an attempt is made to place the concrete at proper consistency it is very hard to secure a satisfactory finish. If, on the other hand, sufficient water is added to make the mix workable, concrete greatly deficient in strength will result. The answer is, have the mix of such workability that it can be placed and finished without using excess water, and the authors believe that this can best be accomplished by having uniformly graded aggregates. This point is discussed here simply to emphasize a condition which is met with in practice, but which the tests did not cover, because, as has been stated, the concretes in all of these sections were of medium consistency, and not necessarily all of the same workability. These tests indicate what would probably result in practice, provided the consistency were rigidly controlled irrespective of the harshness of the concrete mix.

GROUP V*c* (SECTIONS 56–62)—EFFECT OF MORTAR TOP, HYDRATED LIME AND STONE SCREENINGS

Reference has already been made to the condition of section 56, which is a 1 : $1\frac{1}{2}$ mortar top, compared with other sections in which the same mortar is combined as a matrix with several coarse aggregates. The wear of the mortar top is not much greater than that of the related concretes and is remarkably uniform. Section 57, however, which contains a 1 : 3 mortar, has worn excessively, again emphasizing the fact that a 1 : 2 mortar is probably the leanest which should be used.

Three sections, 58, 59, and 60, were constructed in which 12 per cent by volume of hydrated lime, based on the cement, was added to the regular 1 : $1\frac{1}{2}$: 3 mix. Section 58 contained a very hard, tough trap from Wisconsin; section 59, the Martinsburg limestone with Potomac River sand; and section 60, the same stone with the fine Potomac River sand. About the only feature of interest in connection with these tests is the fact that section 60, although containing the fine sand, did not wear as much as corresponding sections in which no hydrated lime was used. Otherwise, the section behaved about the same as corresponding sections without lime.

The two sections containing limestone screenings in place of sand, 61 and 62, did not behave very well. Due to the natural harshness of the concrete it was impossible to secure a proper finish, which has resulted in excessive wear. These two sections illustrate very well the danger of using screenings alone in place of sand unless the screenings are very carefully graded to give concrete which will not be excessively harsh, or unless a sufficient amount of sand is used to supply the lack of fineness found usually in the commercial run of screenings.

GROUP V*d* (SECTIONS 43–45)—EFFECT OF MINE CHATS AND BURNT CLAY

Another illustration of the result of using harsh-working materials is furnished by sections 43 and 44 in which mine chats from Joplin, Mo., were used. Both of these sections have worn excessively, due not to the softness of the aggregates but rather to the fact that the harsh mix prevented a proper finish from being obtained. The sections also furnish evidence indicating a lack of bond between the cement and the aggregates, due possibly to the very smooth surface of the latter which is peculiar to chert. Section 45, in which burnt clay ("Haydite") was used, likewise showed a large amount of wear, about double the average wear of those sections using standard aggregates.

THE RESULTS OF CONTROL TESTS

The control tests include determinations of the crushing strength, transverse strength, modulus of elasticity and resistance to wear as measured by the Talbot-Jones wear test. In this paper, however, the authors have been principally concerned with a discussion of the relations which exist between the wear on the test pavement sections and the physical properties of the aggregates used in them. No attempt will be made, therefore, to discuss in detail at this time the significance of the concrete tests. There are, however, a few salient points to which it may be well to call attention. By referring to Fig. 8, it is immediately apparent that there is no consistent relation between the results of either the compression or the transverse strength tests and the depth of pavement wear. This is particularly noticeable in connection with the study of rock as coarse aggregate in group I. Although the crushing strength of the concrete in this group varies considerably, there is no relation whatever between this property and the depth of wear. The average crushing strength of the concrete in sections 8, 9, and 10 is actually higher than in the concrete in which the very hard aggregates were used.

Nor do we find any relation between wear and strength in the gravel group. While the crushing strength of the concrete in section 19 is low, its modulus of rupture is practically identical with the other concretes in this group. In the case of slag the same condition holds true. Section 39, containing the light slag, in fact, has a higher modulus of rupture than the corresponding sections containing the heavy slag. An interesting point in connection with slag is the high crushing strength developed by the smelter slag. These high values, however, are not reflected in the transverse tests.

About the only feature of interest in connection with the sand, group IV, is the fact that the sand showing the greatest wear has likewise the lowest crushing strength. The results of the control tests in so far as they reflect variations in consistency, time of mix and cement content, shown in group V*a*, are fairly consistent. Variations in gradation, shown in group V*b*, however, apparently have little effect on the strength, at least so far as is indicated by the limited number of tests made. The variation in both crushing and transverse strength is high but not consistent.

The results of the Talbot-Jones wear test likewise appear to give little indication of the actual resistance of the concrete to wear produced by traffic. The authors believe that this is due to the fact that the Talbot-Jones test is not strictly an abrasion test. The shot in the rattler has an appreciable shattering effect, especially at the edge of the block, which is not duplicated in actual traffic.

CONCLUSIONS

Before attempting to draw general conclusions from these tests, it may be well to restate certain premises regarding the volume and character of traffic to which the test pavement has been subjected. These premises follow:

1. That on the average 18-ft. concrete road, approximately 10 per cent of the total traffic moving in both directions passes over a band 6 in. in width at the point of maximum concentration. Therefore, the traffic passing over the test road should be multiplied by at least 10 to obtain the equivalent volume of traffic on an actual pavement.

2. That the comparative resistance of each test section to the surface wear produced by the tire chains, is an indication of the comparative resistance which would be offered by the concrete to wear or disintegration at the edges of exposed joints and cracks under service conditions.

3. That conditions which cause surface wear, such as steel tires, tire chains tracking through snow, etc., are present to such an extent as to make it necessary to give the question of wear consideration in the selection of concrete aggregates.

The authors believe that the data so far secured warrant the following conclusions:

1. That the rate of wear of stone concrete is, in general, not affected by the coarse aggregate provided the coarse aggregate is equal or superior to the mortar matrix in resistance to wear.

2. That excessive wear will result from the use of very soft stone as coarse aggregate even though used in conjunction with a mortar of satisfactory quality. From the results of these comparative tests, it would appear that stone with a percentage of wear over 7.0 should not be used in the wearing course of concrete roads.

3. That gravel concrete, in general, is at least as satisfactory from the standpoint of wear as stone concrete.

4. That gravels consisting essentially of siliceous materials are superior as regards both the amount and uniformity of wear to those containing a preponderance of calcareous fragments.

5. That gravels consisting of rounded particles are as satisfactory from the standpoint of wear as those consisting either wholly or in part of angular or crushed fragments.

6. That small amounts of shale occurring in the coarse aggregate will cause both excessive and uneven wear.

7. That the modified abrasion test for gravel in its present form is not an indication of the wear-resisting properties of coarse aggre-

gates. It is suggested that if the severe impact action of the steel balls were decreased much more indicative results would be secured.

8. That blast-furnace slags should prove satisfactory for use in concrete pavements provided the proportion of light, porous slag is so controlled that the weight per cubic foot will be at least 70 lb.

9. That the presence of large amounts of light, porous fragments in blast-furnace slag will cause excessive wear.

10. That somewhat better results are secured by the use of the smaller sizes of slag.

11. That slag or stone screenings are, in general, unsatisfactory as substitutes for natural sand as fine aggregates in concrete road construction.

12. That the copper and lead-smelter slags used in these tests would make satisfactory aggregates for concrete road construction from the standpoint of wear.

13. That coarse sands, other things being equal, show greater resistance to wear than fine sands.

14. That the so-called "tensile-strength-ratio" test is no indication of the wear-resisting properties of concrete made with these sands.

15. That the Talbot-Jones wear test is not, in general, an indication of the wear which takes place under traffic.

16. That neither the crushing nor the transverse strength of concrete is a measure of its wear-resisting properties.

17. That the addition of hydrated lime in the proportion used in these tests does not affect the wear-resisting properties of concrete.

18. That so far as resistance to wear alone is concerned, increasing the cement content beyond a cement-sand ratio of 1 : 2 does not materially affect the concrete. Leaner mixes, on the other hand, show marked increases in wear.

19. That unusual precautions should be taken in using mine chats or other similar harsh-working materials, so as to increase workability to a maximum and thus make possible a smoother surface finish.

20. That, other things being equal, either an excessively dry or an excessively wet mix will show less resistance to wear than concrete of medium consistency.

DISCUSSION

Mr. Chapman. Mr. Cloyd M. Chapman.[1]—I notice that the authors stated, and it shows all through the test, that plain rubber tire traffic of this type does not seriously wear concrete pavement, but I have heard it argued that high-speed traffic would injure a pavement much more than a slow-speed solid tire. Have you any data on this point?

Further, what was the parting material used to facilitate removal of the plaster casts?

In reference to this slag experiment, using a very light slag: I never saw a slag of that weight per cubic foot that I can recall. Is that very light weight slag aggregate something that is on the market?

Mr. Mattimore. Mr. H. S. Mattimore.[2]—The authors of this paper are entitled to considerable credit for their research work on the wear of concrete pavements. It seems to me that some of the problems solved, as a result of this research, should finally settle discussions regarding the qualities of fine and coarse aggregates for use in concrete pavement work.

In general, the main results are pointed out in the conclusions upon which I should like to base my remarks. For instance, in conclusion No. 2 it is pointed out that extensive wear will result from the use of very soft stone as coarse aggregate. It is a well-known fact that this has actually happened in practice. It is due not only to the softness of the aggregate under abrasion, but such products are likely to be unstable when subjected to the action of traffic and the elements. Further, soft limestones are likely to accumulate a dust coating during crushing, and this condition is especially aggravated during wet weather.

In the conclusions regarding gravel concrete, I believe it would be advisable to combine Nos. 3, 4 and 6 into one conclusion. I do not necessarily agree with the authors, that even the best gravel concrete is as satisfactory as a good stone concrete, but in order to make a satisfactory concrete, gravel must be uniform in quality and be free from shale. A gravel made up of siliceous materials is superior to the ordinary mixed gravel, but usually, especially in the eastern part of the United States, the deposits of siliceous gravels of uniform quality are confined to a few areas. Therefore, in the practical use of stone

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[2] Engineer of Materials, Pennsylvania State Highway Commission.

Mr. Mattimore.

or gravel for use as coarse aggregates in concrete road slabs, the engineers in certain sections prefer the stone, due to the fact that there is more assurance of obtaining a uniform quality than in the ordinary gravel deposit.

I am especially pleased with conclusion No. 13. This should go a long way toward satisfying engineers in the highway field that coarse sands do show a greater resistance to wear than the finer sands.

Conclusion No. 16 is a logical one, in that resistance to wear is an entirely different quality than either transverse or compressive strength.

Conclusion No. 18 is an excellent one for highway engineers to follow, in that an increase of the cement ratio above the 1:2 proportion leads into difficulties, causing excessive shrinkage which results in numerous cracks.

Mr. Crum.

MR. R. W. CRUM.[1]—From the data given in this paper, I seem to have the rather odious distinction of having supplied the worst gravel and the worst limestone used in these tests. It might be fitting to read my alibi into the record, to the effect that these are not materials that have been used in concrete pavement construction. We sent them in partly in the hope, which has been fulfilled, that these tests would reinforce our objections to that particular type of material. This limestone is very soft, having a percentage of wear of from 10 to 15 per cent. We have not used stone anywhere near that soft, but it is very interesting to me in reinforcing our judgment on those particular materials.

I was interested in what Mr. Mattimore said concerning the richness of the mortar used by Mr. Jackson in the tests, regarding some danger of excessive shrinkage when excessively rich mortars are used. It might be interesting to note that some experience we have had, not so much with rich mortars as rich concrete, puts a little different light on that. In our practice we often have to use considerably higher ratios of sand to coarse aggregate than is customary in a good many of the states, and our proportioning methods, while increasing the amount of cement in the total aggregate, will decrease the amount of cement in the mortar. If we are making a mixture containing perhaps 60 per cent of sand in the aggregate, instead of having a 1:2 mortar we have something like a 1:2$\frac{1}{4}$ mortar. We find in such mixes that the cracks are more in evidence than in the leaner mixes. There is quite a showing in this case that it is the effect of the ratio of cement to the total aggregate rather than of the cement to the fine aggregate.

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[1] Engineer of Materials and Tests, Iowa State Highway Commission.

Mr. Abrams. MR. D. A. ABRAMS.[1]—Mr. Jackson has shown the variation in the wearing resistance of the concrete due to the size and grading of the sand and pointed out that there was no relation between the tensile strength of the mortars and the wearing resistance of the concrete. There may be a little misapprehension as to the true relation here. In the sand mortar tests, the entire aggregate is made up of sand; in concrete the sand is only, say, one-third of the total aggregate. Consequently, we might expect that the effect due to the qualities of the sands would be only one-third of the total difference. In other words, with two sands giving strength-ratios of 70 and 130 per cent, we might expect only such differences in the concrete strength as would be represented by strength-ratios of 90 and 110. In other words, the spread in values would be very much reduced in the concrete tests. A great many of our tests have shown this relation.

In Fig. 7 of the paper, in which the results of the wear test with chains are plotted, it appears that the discrepancies in these values of the wear are somewhat due to the amount of wear. In other words, if we take the very early stages of the test, we do not get the same arrangement of the test specimens as we do if we take a later stage. For example, if we consider the black lines only, we find that the ones which are highest on that diagram are not the ones which show the maximum wear at later stages of the test. The point I want to bring out is that that really represents about the stage of wear that would be obtained in using the Talbot-Jones rattler, so we should not expect that the total wear on the slabs would be proportional to the wear at early stages.

Mr. Rea. MR. A. S. REA.[2]—I should like to refer to the abrasion test on gravel. Mr. Jackson stated they found no relation between the modified abrasion test and the wear test on the concrete. I realize that this test has not proved satisfactory in some states for the gravels which are being used. This was pointed out in Mr. Jackson's paper with the so-called "sugar quartz gravel." However, for the gravels which we have in our state, some of which are more or less variable in quality, containing some very hard pebbles and some extremely soft sandstone pebbles, we have found this test very satisfactory. I believe, however, that it is subject to improvement, and it is possible that the test can be modified so that the results obtained will give a better indication of the value of the gravel as an aggregate in concrete.

Mr. McMillan. MR. F. R. MCMILLAN.[3]—I should like to ask one question. Mr. Jackson enumerated in his conclusions three premises. I should like

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[2] Engineer of Tests, Ohio Department of Highways and Public Works.
[3] Associate Engineer, Structural Materials Research Laboratory, Lewis Institute, Chicago, Ill.

Mr. McMillan. to ask the basis of that second premise, whether it is based on any of the results of the tests or simply on experience and observations of the surface of roads.

Mr. Jackson. MR. F. H. JACKSON.—I shall endeavor to answer the questions asked by Mr. Chapman in the order in which they were given.

The Bureau has no data regarding the effect of speed of either pneumatic or solid tires on the wear of concrete pavements. The tests described in this paper were, of course, made at practically a constant speed (20 m.p.h.) using solid tires only. I fail to see, however, just why a high-speed pneumatic tire would cause any greater, if as great, surface wear than a slow-speed solid tire. It must be remembered that we are considering *surface wear* only, and not impact.

In reply to Mr. Chapman's second question, we used an ordinary lubricating oil as the parting material for the plaster casts. This oil has proved entirely satisfactory for the purpose.

With regard to the light slag, the sample used in the experiment was hand picked from a commercial supply. This does not mean, however, that it was impossible to obtain such a light slag commercially. I have seen slag produced commercially which weighed less than 60 lb. per cu. ft. It would, however, have been rather difficult to obtain it on short notice for these tests, which was the reason why the sample used was hand picked.

Relative to the point brought out by Mr. Abrams in regard to the relation between the tensile strength ratio test and the amount of surface wear the explanation given by him was discussed at considerable length in the paper. I believe that the range in tensile strength ratio results in the mortar test is far greater than would be the case if the mortars were incorporated in concrete. This is probably the reason why we did not get any better relation between the wear on the concrete pavement and the tensile strength ratio test. On the other hand, we deemed it advisable to sound a warning with regard to this test, because so many engineers are in the habit of taking the tensile strength ratio as an absolute indication of the value of the sand apart from any other test. I do not believe that this is possible. This test is only of value when used in conjunction with other tests on sand. It is extremely inadvisable to attempt to differentiate between a satisfactory and an unsatisfactory sand by the use of this test alone.

In answer to Mr. McMillan, the second premise enumerated in the paper was not based upon the results of any tests. It was more or less theory supplemented, however, by experience gained as the result of observations of the actual behavior of concrete road surfaces under traffic.

PROPERTIES OF GYPSUM TILE[1]

By J. M. Porter[2]

Committee C-11 on Gypsum of the American Society for Testing Materials submitted in 1923 Tentative Specifications for Gypsum Tile or block. When these specifications were prepared few data were available on which to base the requirements and accordingly the U. S. Bureau of Standards was requested to supply additional information relative to the properties of gypsum tile or block. The investigation described in this paper was accordingly undertaken by the U. S. Bureau of Standards.

Introduction

Gypsum tile is a building unit used for non-bearing interior construction and as a protection for columns, elevator shafts, etc., against fire. Certain sizes are sometimes split and used for furring purposes. They consist of gypsum with or without an aggregate, the aggregate most commonly used being wood fiber. Wood chips, sawdust and sand are other aggregates sometimes employed. Its function is most important, since it is largely by virtue of the nature and amount of aggregate that the brittleness of the gypsum is reduced, which reduction is so necessary considering the conditions under which the tile are used. The nominal thickness of gypsum tile is 2, 3, 4, or 6 in. The nominal width is 12 in. and the nominal length 30 in., although some tile 24 in. in nominal length have been placed on the market.

The tile are cast in molds. One side is usually made more or less smooth and with indentations of some form so that inches in length can be read directly. The other side is scored while soft by scratching the surface with a stiff brush, thus producing a better surface for the reception of plaster.

Gypsum tile are erected on edge in a gypsum mortar in such a manner that the vertical joints are staggered or broken by every other row of tile.

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[1] Published by permission of the Director of the Bureau of Standards, U. S. Department of Commerce.

[2] Assistant Chemical Engineer, U. S. Bureau of Standards, Washington, D. C.

DETERMINATION OF PROPERTIES

Samples of tile were received from about 90 per cent of the manufacturers. Each set of specimens from which an average was taken consisted of five individual tile. The determinations made upon each tile included the composition, dimensions, core volume, weight, expansion, absorption, rate of absorption, shell thickness, compressive strength, and transverse strength.

The chemical composition, which included filler, was determined in accordance with the Standard Methods of Testing Gypsum and Gypsum Products of the American Society for Testing Materials.

Measurements of the dimensions, length, width and thickness were made to the nearest $\frac{1}{32}$ in. For length, two measurements were made upon each tile. For width, measurements were made at five points, 5, 10, 15, 20, and 25 in. from the end. For thickness, one measurement was made at the center of each end, and at points near each edge 10 and 20 in. from the end.

The core volume was determined by noting the weight necessary to fill the core spaces, of washed sand, which would all pass a No. 20 sieve and be retained on a No. 30 sieve, and whose weight per unit volume had been previously determined.

Each tile was weighed to the nearest ounce. Before weighing, the tile were allowed to stand several days in the laboratory in order to dry out as thoroughly as possible without heating.

Expansion was determined by means of a 12-in. strain gage. The results were reported in inches of expansion per inch of length, the initial reading being taken with the tile dry and the final reading taken after the tile had been immersed for 24 hours in water whose temperature was between 70 and 80° F.

In determining absorption the tile were dried at room temperature and weighed. They were then immersed for two hours in water at a temperature of from 70 to 80° F., the excess water wiped off, and the tile reweighed. The absorption was calculated on the dry weight.

The rate of absorption is a new determination, but one which it is believed will give a much more accurate indication as to whether or not the tile offer the proper suction for the application of a plaster than that given by the results of total absorption. Measurements were made by sealing onto the face of the tile a $1\frac{1}{2}$-in. glass cylinder, graduated in cubic centimeters. Into this was poured 250 cc. of water at a temperature of approximately 70° F. The amount of water absorbed per minute was taken as the rate of absorption.

The minimum thickness of shell on both the side and edge of the tile was measured to the nearest $\frac{1}{32}$ in.

Instead of making the compressive strength determinations in the usual manner by subjecting a whole tile to the test, specimens the full thickness of the tile and 15 sq. in. in bearing area, with a height of 12 in. were cut from the tile and used for test purposes. If the bearing surfaces were unduly rough they were capped with a thin layer of gypsum.

Transverse strength measurements were made with a span of 24 in., applying the load at midspan with the tile laid flatwise. This test was included in an effort to arrive at a test which would serve as a guide as to the breakage to be expected incidental to handling. It was thought that the results of the transverse tests would be of more value than the values obtained in the compression test.

It might be well to note here that the values obtained for the modulus of rupture are only approximately correct. This is due to the fact that the cross-section of the tile or block under test has been treated as a rectangle without allowance having been made for the core spaces, which run the full length of the tile. This results in a slight error in the value for the moment of inertia. Assuming, however, the core spaces to be 1.5 in. in diameter, which is about the average for a 3-in. tile, and the core spaces to be four in number, which is usually true, the error is only 3.67 per cent. As the material itself would give results which would vary considerably more than this, to facilitate the calculations, it is seen that the failure to take the area of the core spaces into consideration is not serious.

DISCUSSION OF TESTS

In Table I the results of the tests have been summarized into as few figures as possible.

For gypsum tile to be satisfactory it should conform to the following requirements:

Dimensions.—The present specifications allow a tolerance in length of $\frac{3}{8}$ in.; in height of $\frac{1}{4}$ in.; in thickness of $\frac{1}{8}$ in. The results of the measurement show 95 per cent of the tile to pass these requirements. In view of the manner in which gypsum tile are used a more rigid requirement does not appear justifiable.

Core Volume.—Increase in core volume reduces the weight, compressive strength and fire-resisting qualities of the tile. A maximum allowable core volume seems desirable but not a minimum, as this is controlled by the weight which in turn is an economic feature.

TABLE I.—RESULTS OF TESTS ON GYPSUM PARTITION TILE.

Brand	Length			Width			Depth		
	Average Length, in.	Individual Variation from Average, in.		Average Width, in.	Individual Variation from Average, in.		Average Depth, in.	Individual Variation from Average, in.	
		Maximum	Mean		Maximum	Mean		Maximum	Mean
No. 1	30.20	0.125	0.042	12.06	0.0600	0.020	3.080	0.080	0.030
No. 2	30.12	0.054	0.014	12.07	0.0500	0.026	3.076	0.174	0.031
No. 3	29.91	0.090	0.041	11.96	0.1650	0.046	2.960	0.165	0.038
No. 4	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
No. 5	30.18	0.0625	0.0325	12.02	0.0690	0.015	3.125	0.125	0.033
No. 6	[a]	[a]	[a]	12.08	0.1042	0.064	3.086	0.086	0.039
No. 8	30.07	0.0729	0.0416	12.06	0.0600	0.007	3.057	0.130	0.055
No. 9	30.07	0.0687	0.0340	12.00	0.0620	0.009	2.995	0.130	0.047
No. 10	30.05	0.0750	0.0470	12.01	0.1100	0.024	2.977	0.148	0.048
No. 11	30.10	0.0375	0.030	12.00	0.000	0.000	4.033	0.0958	0.0502
No. 12	30.12	0.0547	0.0136	12.05	0.1328	0.0507	4.027	0.0980	0.0384
No. 13	30.06	0.1875	0.0750	12.03	0.1550	0.0612	4.037	0.1625	0.0575
No. 14	30.03	0.0875	0.0375	12.07	0.0725	0.0462	3.945	0.1800	0.0556
No. 15	30.16	0.1082	0.0794	12.04	0.1031	0.0467	4.018	0.1066	0.0456
No. 16	30.11	0.1437	0.0600	12.12	0.1171	0.0668	4.034	0.0942	0.0434
No. 17	29.96	0.0830	0.0556	12.05	0.2042	0.0988	4.000	0.1250	0.0347
No. 18	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
No. 24	30.10	0.0466	0.0233	12.00	0.1198	0.0338	3.9895	0.1355	0.0632
No. 25	30.18	0.1328	0.0547	12.01	0.070	0.0273	6.020	0.1050	0.0287
No. 26	29.97	0.0320	0.0312	11.93	0.064	0.0497	5.996	0.0166	0.0044
No. 27	30.21	0.0313	0.0312	12.00	0.066	0.0219	6.034	0.2161	0.1124
No. 28	30.12	0.0562	0.0112	12.00	0.125	0.025	5.979	0.1459	0.0486
No. 7	[a]	[a]	[a]	12.06	0.000	0.000	2.101	0.0390	0.0293
No. 19	30.09	0.0937	0.0394	12.01	0.047	0.022	2.227	0.2270	0.0533
No. 20	30.08	0.0833	0.0416	12.01	0.052	0.017	2.023	0.1021	0.0168
No. 21	30.04	0.0390	0.0293	12.00	0.057	0.009	2.082	0.0819	0.0417
No. 22	29.59	0.0936	0.0417	12.07	0.072	0.034	2.016	0.0452	0.0259
No. 23	29.86	0.0763	0.0200	11.99	0.125	0.024	2.031	0.0938	0.0374
No. 29	30.06	0.0625	0.0000	12.02	0.096	0.042	2.104	0.1459	0.0486

Brand	Core Space, cu. in.			Weight per Block, lb.			Modulus of Rupture, lb. per sq. in.		
	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average
No. 1	282.5	269.0	277.3	24.25	23.19	23.86	158.3	117.	138.7
No. 2	207.5	187.0	192.1	32.125	27.437	30.312	193.3	150.	173.0
No 3	230.0	218.0	224.3	25.56	24.81	25.08	160.0	93.3	127.7
No. 4	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
No. 5	290.0	284.0	286.0	24.93	24.00	24.41	168.3	120.0	149.4
No. 6	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
No. 8	283.0	280.0	281.7	22.68	22.12	22.20	166.6	93.3	131.6
No. 9	302.0	297.0	299.4	23.93	22.75	23.35	185.0	106.6	147.3
No. 10	338.0	334.0	336.0	23.12	22.25	22.61	150.0	53.3	96.4
No. 11	456.0	452.0	454.8	30.56	29.25	30.11	129.0	103.0	116.0
No. 12	429.0	424.0	426.0	35.25	32.56	33.70	137.0	137.0	137.0
No. 13	525.0	510.0	517.6	27.125	23.68	25.50	114.0	75.0	89.3
No. 14	433.0	433.0	433.0	34.00	31.50	32.95	115.0	103.0	109.6
No. 15	423.0	416.0	419.0	34.50	32.37	33.43	193.0	172.0	183.5
No. 16	402.0	397.0	400.7	36.25	31.75	33.51	150.0	113.0	129.0
No. 17	219.0	211.0	214.3	37.25	35.50	36.14	234.0	141.0	183.3
No. 18	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
No. 24	362.0	355.0	360.2	36.68	33.50	35.23	135.0	109.0	117.0
No. 25	592.0	583.0	588.2	53.68	51.06	51.93	136.0	91.6	112.7
No. 26	629.0	629.0	629.0	46.12	41.62	44.10	35.0	85.0	85.0
No. 27	772.0	772.0	772.0	39.44	39.44	39.44	91.0	91.0	91.0
No. 28	590.0	579.0	584.2	57.25	51.81	54.12	166.3	101.5	127.9
No. 7	.....	.....	.....	[a]	[a]	[a]	[a]	[a]	[a]
No. 19	.....	.....	.....	27.43	25.75	26.51	277.0	180.0	228.5
No. 20	.....	.....	.....	25.00	24.31	24.67	248.0	248.0	248.0
No. 21	.....	.....	.....	24.56	20.75	22.62	251.0	210.0	226.3
No. 22	.....	.....	.....	25.93	23.12	24.47	143.0	143.0	143.0
No. 23	.....	.....	.....	20.87	20.37	20.66	236.0	191.0	211.4
No. 29	.....	.....	.....	27.87	26.62	27.18	243.0	217.0	225.6

[a] Broken in transit.

TABLE I (*Continued*)

Brand	Compressive Strength, lb. per sq. in.			Absorption, per cent			Least Shell Thickness, in.		Expansion, 0.001 in. per Inch, 24 Hours Immersion
	Maximum	Minimum	Average	Maximum	Minimum	Average	Side	Edge	
No. 1	140.0	76.6	109.4	53.5	44.3	50.72	.....	.....	Not measured
No. 2	148.0	69.3	115.6	55.0	42.5	48.7	.....	.....	
No. 3	163.0	96.0	139.0	62.0	52.0	55.9	.....	.....	
No. 4	190.0	124.0	150.0	41.8	35.2	38.6	.....	.....	
No. 5	210.0	93.7	166.0	61.2	58.2	60.4	0.538	0.925	
No. 6	370.1	208.1	289.1	60.5	52.0	56.3	0.729	1.062	
No. 8	225.0	108.0	161.6	61.6	38.3	51.9	0.575	1.125	
No. 9	211.0	165.0	183.2	61.0	52.2	56.5	0.475	1.075	
No. 10	245.0	83.5	158.1	66.0	57.2	59.6	0.562	1.250	
No. 11	159.0	108.0	143.2	57.0	52.3	54.0	0.713	1.162	0.94
No. 12	179.0	90.0	134.4	51.0	42.0	47.4	0.700	1.212	1.40
No. 13	151.0	71.2	98.1	75.7	61.5	67.8	0.525	1.050	0.41
No. 14	160.0	106.5	127.3	54.6	49.4	52.3	0.650	1.175	6.55
No. 15	193.0	151.0	167.5	49.0	47.2	48.3	0.750	1.109	Not measured
No. 16	147.0	130.0	141.0	54.7	44.0	50.0	0.762	1.050	
No. 17	344.0	238.0	297.0	53.0	47.4	50.4	0.875	1.234	
No. 18	149.0	135.0	143.3	85.0	62.5	72.8	0.875	1.437	
No. 24	89.3	73.4	80.9	50.1	45.0	47.9	0.800	1.199	1.41
No. 25	177.0	133.0	155.8	51.6	48.3	50.7	0.781	0.969	1.00
No. 26	149.0	86.5	118.9	65.8	54.0	59.5	0.625	0.687	0.15
No. 27	150.0	118.0	134.0	72.7	63.0	66.8	0.729	0.875	1.19
No. 28	221.0	181.0	192.0	56.3	44.5	50.1	0.837	1.025	0.25
No. 7	494.0	335.0	399.0	73.0	68.0	70.8	.....	.....	....
No. 19	788.0	655.0	714.6	50.0	47.4	49.1	.....	.....	3.12
No. 20	647.0	508.0	601.4	43.3	41.2	42.3	.....	.....	0.60
No. 21	600.0	248.0	403.4	69.5	53.0	61.1	.....	.....	1.04
No. 22	478.0	265.0	389.8	51.6	41.7	46.7	.....	.....	1.08
No. 23	416.0	345.0	377.5	64.1	62.1	63.3	.....	.....	1.08
No. 29	518.0	418.0	459.2	41.7	38.6	40.4	.....	.....	0.69

Brand	Rate of Absorption on 1½ in. Diameter Surface, cc.								Chemical Analysis								
	First Minute	Second Minute	Third Minute	Fourth Minute	Fifth Minute	Sixth Minute	Seventh Minute	Eighth Minute	Moisture, per cent	Combined water, per cent	Insoluble in 1 : 9 HCl, per cent	Lime, CaO, per cent	Sulfuric Anhydride, SO_3, per cent	Iron Oxide, Fe_2O_3, per cent	Carbon Dioxide, CO_2, per cent	Filler, per cent	Gypsum, $CaSO_4 2H_2O$ (calculated), per cent
No. 1	..	..	..	..	..	..	..	..	0.30	18.02	6.22	29.92	41.47	0.33	1.04	0.86	86.3
No. 2	..	..	..	..	..	..	..	..	0.34	14.00	5.58	29.62	32.59	0.11	8.76	1.06	67.0
No. 3	..	..	..	..	..	..	..	..	0.40	17.80	3.18	31.58	43.87	0.07	0.80	0.77	85.2
No. 4	..	..	..	..	..	..	..	..	0.40	15.26	5.24	31.56	40.10	0.16	2.44	0.00	73.0
No. 5	..	..	..	..	..	..	..	..	0.36	16.50	2.46	31.18	41.58	0.06	2.36	1.33	79.0
No. 6	..	..	..	..	..	..	..	..	0.11	19.15	0.46	32.38	44.88	trace	0.63	1.79	91.6
No. 8	..	..	..	..	..	..	..	..	0.14	19.06	2.40	31.62	43.85	0.05	0.60	1.10	91.2
No. 9	..	..	..	..	..	..	..	..	0.12	14.92	2.76	30.80	35.02	0.05	9.24	0.65	71.5
No. 10	..	..	..	..	..	..	..	..	0.12	15.74	3.16	31.16	39.57	0.18	5.06	2.21	75.3
No. 11	14	10	8	10	9	9	9	10	0.14	19.06	2.40	31.62	43.85	0.05	0.60	1.10	91.2
No. 12	14	11	9	10	8	9	9	8	0.12	15.74	3.16	31.16	39.57	0.18	5.06	2.21	75.3
No. 13	24	15	14	13	14	13	11	..	0.36	16.50	2.46	31.18	41.58	0.06	2.36	1.33	79.0
No. 14	27	19	16	17	17	16	..	..	0.12	14.92	2.76	30.80	35.02	0.05	9.24	0.65	71.5
No. 15	10	6	5	5	6	6	6	6	0.30	18.02	6.22	29.92	41.47	0.33	1.04	0.86	86.3
No. 16	..	..	..	..	..	..	..	..	0.34	14.00	5.58	29.62	32.59	0.11	8.76	1.06	67.0
No. 17	..	..	..	..	..	..	..	..	0.40	17.80	3.18	31.58	43.87	0.07	0.80	0.77	85.2
No. 18	14	10	9	11	10	11	11	11	0.11	19.15	0.46	32.38	44.88	trace	0.63	1.79	91.6
No. 24	11	6	7	6	6	6	6	7	0.00	17.76	4.66	30.98	42.10	trace	2.19	1.04	85.0
No. 25	29	20	19	20	13	18	..	..	0.34	14.00	5.58	29.62	32.59	0.11	8.76	1.06	67.0
No. 26	28	20	18	19	17	15	14	..	0.36	16.50	2.46	31.18	41.58	0.06	2.36	1.33	79.0
No. 27	11	6	7	7	7	7	6	8	0.11	19.15	0.46	32.38	44.88	trace	0.63	1.79	71.5
No. 28	19	13	12	13	12	11	10	8	0.00	17.76	4.66	30.98	42.10	trace	2.19	1.04	85.0
No. 7	..	..	..	..	..	..	..	..	0.11	19.15	0.46	32.38	44.88	trace	0.63	1.79	91.6
No. 19	13	12	13	12	15	15	15	16	0.12	15.74	3.16	31.16	39.57	0.18	5.06	2.21	75.3
No. 20	31	22	24	24	17	15	16	..	0.14	19.06	2.40	31.62	43.85	0.05	0.60	1.10	91.2
No. 21	9	5	6	7	7	7	8	8	0.12	14.92	2.76	30.80	35.02	0.05	9.24	0.65	71.5
No. 22	26	18	19	19	18	10	14	..	0.34	14.00	5.58	29.62	32.59	0.11	8.76	1.06	67.0
No. 23	30	22	24	26	..	..	...	..	0.40	17.80	3.18	31.58	43.87	0.07	0.80	0.77	85.2
No. 29	9	7	6	7	6	6	6	7	0.11	19.15	0.46	32.38	44.88	trace	0.63	1.79	91.6

Modulus of Rupture.—The feasibility of a requirement for modulus of rupture has been discussed at length in a previous paragraph and it seems that a minimum modulus of rupture should be specified.

Compressive Strength.—The present specifications require a compressive strength of at least 75 lb. per sq. in. Only three tile out of 145 failed to meet this requirement. As gypsum tile are designed primarily for non-bearing partitions there is no reason for a more stringent requirement on a material which is without doubt sufficiently strong to withstand any use for which it is intended.

Total Absorption.—As might be expected, with an increase in absorption a decrease occurs in the compressive strength and the weight of gypsum tile. The results of the tests bear this out consistently. Use might be made of this relation to decrease the number of tests with a decrease in testing costs, by the substitution of a maximum and minimum requirement for absorption in place of those for strength and weight.

Rate of Absorption.—The results of the rate of absorption tests indicate the desirability of excluding tile which cannot be satisfactorily plastered. With this in mind it is believed that a rate of absorption requirement is justified.

Shell Thickness and Gypsum Content.—It is upon the shell thickness and gypsum content that the property of fire-resistance of gypsum tile depends. For this reason measurements were made of these properties and inclusion of them in a specification for gypsum tile is deemed necessary.

Expansion.—Although the ideal tile should be one in which the expansion and contraction with atmospheric changes would be the same as the movements of the plaster under the same conditions, such tests are not considered practical. These tests were made solely to gain an idea of the variations existing in commercial tile.

TEST OF GYPSUM TILE PARTITION

In order to study the behavior of gypsum tile upon a basis comparable to conditions in actual practice, a partition was erected on June 2, 1920, of gypsum tile, 3 in. thick by 12 in. wide by 30 in. long, laid on edge in gypsum mortar. Each tile contains four cores 1.5 in. in diameter, running the full length of the tile. The scratch and brown coats were applied on both sides of the partition on June 14, and the white coat on June 17.

The partition extends in an east and west direction, on the second floor of the Industrial Building of the U. S. Bureau of Standards, Washington, D. C. The partition is 10 ft. high by 21 ft. 9 in. long, with an average thickness, including plaster, of $4\frac{3}{8}$ in. It is solid with the exception of four small supply pipes running through the partition near the lower western corner and a thermostat pipe extending from the floor upwards for about five feet embedded in the partition about nine feet from the western end.

Immediately under the partition is a horizontal reinforced concrete beam, 24 in. deep by 16 in. wide. The partition is centered on this beam, and a similar beam extends across the top of the partition. The beams are supported at both ends by concrete columns, which are carried on the foundation and are part of the main structure of the building. The column at the western end of the partition is part of the outside wall of the building but is protected from the weather by a brick veneer; that at the eastern end is entirely enclosed.

In order to measure the deflection of the upper beam, six small mirrors were pasted on the side of the beam, near its lower edge. No. 1 mirror is 3.5 in. from the eastern end of the beam; No. 6 mirror is the same distance from the western end; and the others are spaced equi-distant along the length of the beam. The surface of each mirror is graduated with lines 0.02 in. apart. Between each end mirror and the adjacent end of the beam, steel plugs were attached, projecting out from the beam. A fine silk cord was laid across these plugs and made taut by tying weights to each end, thus stretching the cord directly in front of the mirrors. Since the plugs are close to the columns supporting the beam, they, and therefore the cord, may be assumed as fixed. The relative motion of any part of the beam can be read from the graduated scale on the mirror. With the aid of a pocket flashlight and a jewelers' magnifying glass, movements of 0.01 in. can easily be noted.

To measure the deflections of the lower beam, small steel disks were pasted to the ceiling, above and immediately in front of each mirror. Vertically beneath each disk, a steel plug was set in the floor, a small conical hole being sunk in each plug. Extreme care was taken to keep these holes covered and free from dirt. A pole of the proper length and 1.5 in. square was cut of thoroughly seasoned mahogany and further protected by two coats of waterproof varnish. It was stiffened by binding to its four sides pieces of 1 by $\frac{1}{8}$-in. strap iron, extending about three-fourths of its length. The lower end of the pole was provided with a steel shoe, pointed to fit into the conical holes in the floor plugs. A micrometer dial was rigidly attached to the upper end in such a way that the rubber tip of the dial can be easily centered on the steel disks on the ceiling. The dial reads to 0.01 in. To allow for variation in the length of the pole, it was assumed that the western end of the beam did not move, and the readings taken at the other five places have been corrected on this assumption.

Brass plugs were inserted over the entire surface of the partition, spaced 20 in. apart, both horizontally and vertically. Changes in distance between these plugs were measured with a strain gage reading to 0.0002 in. The vertical motion of the partition was found by adding the five readings taken between plugs in a vertical line. There are 14 such lines of plugs. Similarly, the horizontal motion is indicated by the sum of 14 readings between plugs in a horizontal line, there being five such lines. This method possibly increased the experimental error, but this should be more than compensated for by the much greater accuracy of the individual readings.

At present, there are corner cracks extending along both ends of the partition and across the top. These extend through the plaster, on both sides of the partition. This is definite evidence of a differential movement between the partition and the surrounding concrete members.

At the upper eastern corner, there is a diagonal crack, extending through the plaster on both sides of the partition. Apparently this crack started next to the wall at about the level of the top course of blocks, and extended diagonally upward to the beam. It seems as though the partition had moved downward, sliding along the columns, but that the upper block stuck and stayed in place.

The evidence from the readings taken as described above seems conclusive that the corner cracking and the diagonal crack in the plaster cannot be blamed upon the gypsum tile of which the partition is constructed, nor on the workmanship. They seem to be due entirely to the motion of the structural members of the building, indicated by the readings. Further evidence of this motion of the structural members is found in a similar diagonal crack which has developed in an adjacent parallel partition of entirely different construction.

But in view of the fact that the above investigation was conducted upon one partition only, no attempt should be made, based upon the results obtained, to draw definite conclusions as to the behavior of similar partitions.

Acknowledgment.—The author wishes to make acknowledgment of the assistance of W. E. Emley of the Bureau of Standards and of C. J. Whittlesey, Research Fellow, the Gypsum Industries.

FACTORS AFFECTING BRICK MASONRY STRENGTH[1]

By S. H. Ingberg[2]

In connection with a series of fire tests of brick walls, smaller wall sections were built in parallel with the test walls[3] and weighed at intervals to check the moisture loss during the seasoning period, the walls subjected to fire tests being seasoned until a large portion of the free water had been given off. After having served their purpose in this particular, the smaller wall sections were tested in compression. Some of them were stored for periods up to one year after the fire test on the companion wall, to obtain any further moisture loss that might occur. Their age had therefore a considerable range, although none was tested earlier than 69 days after building, so the effect of age as causing variation in the strength of the brickwork was probably not large, nor do the results obtained indicate any general increase of strength with age, except where the bricks were laid in lime mortar.

The range in strength, absorption and surface properties between the different kinds of brick used was quite large, and while the tests were not of sufficient extent to enable exact quantitative conclusions to be drawn, it is believed that the results give valuable indications with reference to the properties of the brick that affect the strength of the masonry.

Description of Brick and Masonry

Of the five kinds of brick included, the Western surface-clay brick was of calcareous clay, burning to a uniform light porous body of medium compressive strength and relatively high transverse strength. It was made by the stiff-mud process, being forced through a die and wire-cut on the ends. The four sides were smooth and covered with particles of fine kiln dust in varying amounts. The Eastern surface-clay brick was dark red and of medium strength and density. The surface was gritty from the fine sand used in surfacing the brick molds. The shale brick had the dense structure and high strength typical of shale. It was molded by being forced through the die and wire cut on the wide faces, which left them moderately rough, pitted and ridged. The concrete brick was made of portland cement and siliceous sand in the proportion of 1:5 by volume, and was formed by being cut from the bottom of an 8-ft. column of the wet mix by horizontal and vertical knives. The surface was uniformly rough from the method of forming and from protruding particles of the aggregate. The sand-lime brick No. 1 was made from lime and fine sand crushed from high-silica sandstone, molded under pressure and hardened in steam at 130 to 135-lb. pressure. The resulting surface was uniformly hard and smooth. The sand-lime brick No. 2 was made of lime and bank sand and hardened at 120-lb. steam pressure, the surface being moderately rough from protruding sand grains.

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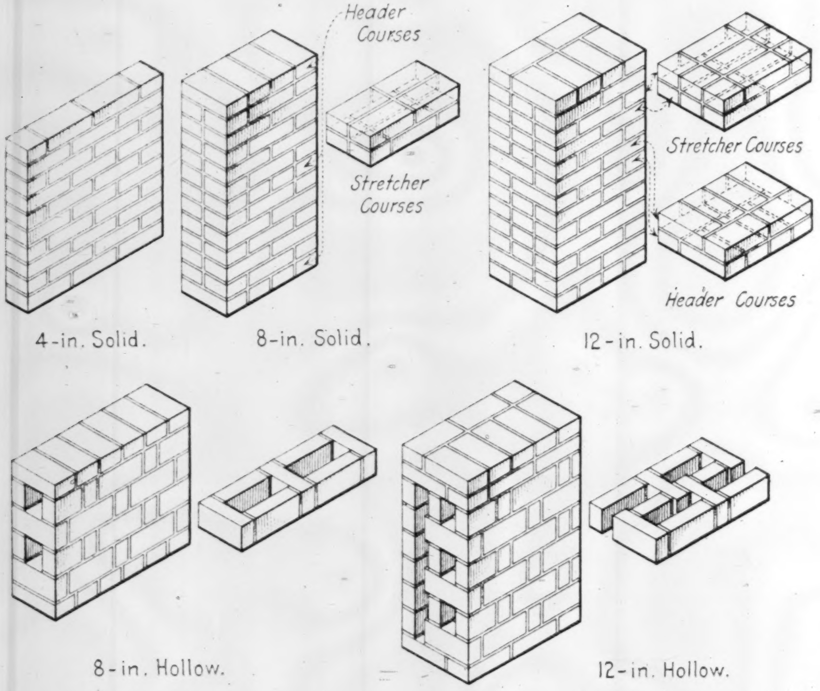
[1] Published by permission of the Director of the Bureau of Standards, U. S. Department of Commerce.

[2] Physicist, U. S. Bureau of Standards, Washington, D. C.

[3] They were of the same design and material as the larger walls and built by the same workmen.



4-in. Solid. 8-in. Solid. 12-in. Solid.

8-in. Hollow. 12-in. Hollow.

FIG. 1.—Details of Masonry Specimens.

A summary of strength and absorption properties of the different kinds of brick is given in Table I, the absorption being determined by the 5-hour boiling method.

Sketches of typical wall sections tested are given in Fig. 1. In the solid 8- and 12-in. walls, the brick were laid in common or American wall bond with five stretcher courses for each header course. The hollow (Ideal all rowlock) walls were laid with brick on edge and alternate headers and stretchers in each course. Header courses of brick were laid flat on top and bottom of each specimen. The walls of 12-in. nominal thickness were actually between 12 and 13 in., depending on the size of the brick and the thickness of mortar joints. The average height of the specimens tested in compression was 30 in. and the average length 21 in.

The workmanship was comparable with that obtaining for the larger test walls, having been constructed by the same men. These walls were built on a contract basis by the lowest bidder. The rate of laying brick in 8- and 12-in. solid walls averaged 1230 brick per mason per 8-hour day. The horizontal joints were fairly well filled and the vertical joints were, on the average, a little more than half filled.

TABLE I.—PROPERTIES OF INDIVIDUAL BRICK

Results are the average of from 5 to 30 tests.

Kind of Brick	Compressive strength, lb. per sq. in.		Modulus of Rupture, flatwise, lb. per sq. in.	Absorption, per cent
	On edge	On side		
Western surface clay	2166	2967	1155	23.1
Eastern surface clay (first shipment)	2497	3328	824	15.8
Eastern surface clay (second shipment)	2123	3185	1198	15.6
Shale	6577	8393	2121	6.7
Concrete	1486	3129	641	13.4
Sand-lime No. 1	4744	4545	1142	16.5
Sand-lime No. 2 (first shipment)	1688	1840	463	21.0
Sand-lime No. 2 (second shipment)	2546	3008	846	24.3

TEST METHODS AND EFFECTS

The wall sections were capped with gypsum, or portland cement and gypsum caps, placed and hardened between the heads of the 1,000,000-lb. hydraulic testing machine in which the tests were made. The readings of this machine were compared by means of a comparison bar with those of calibrated lever machines, before and after the series of tests, the accuracy with which the loads at failure were determined being indicated to be within 2 per cent.

The first definite sign of approaching failure was the appearance of vertical cracks in the brick, generally first in the header courses. There were no signs of compression failure of individual brick until very near failure of the masonry. The cracking of the headers in the 8-in. walls caused the two 4-in. halves of the wall to separate on the longitudinal center joint, a considerable increment of load obtaining after separations of $\frac{1}{8}$ in. or more had occurred. This statement holds

TABLE II.—COMPRESSIVE STRENGTH OF MASONRY.

Sections of walls from 15 to 27 in. in length and from 22 to 40 in. in height.

Test	Kind of Brick	Age of Masonry, days	Nominal Wall Thickness, in.	Mortar[a]	Strength of Masonry, lb. per sq. in.	Ratio of Masonry Strength to Brick Strength		
						Compressive Strength, on edge	Compressive Strength, on side	Modulus of Rupture, flatwise
				8 AND 12-IN. SOLID WALLS				
No. 1	Western surface clay	156	8	$1P:1\frac{1}{4}L:6S$	527	0.243	0.178	0.456
No. 3	Western surface clay	159	8	$1P:1\frac{1}{4}L:6S$	529	0.244	0.178	0.458
No. 7	Western surface clay	157	12	$1P:1\frac{1}{4}L:6S$	483	0.223	0.163	0.418
					Av. 513	0.237	0.173	0.444
No. 9	Eastern surface clay	146	8	$1P:1\frac{1}{4}L:6S$	855	0.343	0.257	1.037
No. 10	Eastern surface clay	231	12	$1P:1\frac{1}{4}L:6S$	738	0.296	0.222	0.896
					Av. 796	0.320	0.240	0.966
No. 14	Shale	80	8	$1P:1\frac{1}{4}L:6S$	1659	0.252	0.198	0.782
No. 15	Shale	98	8	$1P:1\frac{1}{4}L:6S$	1416	0.215	0.169	0.668
					Av. 1538	0.234	0.184	0.725
No. 21	Concrete	72	8	$1P:1\frac{1}{4}L:6S$	844	0.568	0.270	1.316
No. 22	Concrete	313	8	$1P:1\frac{1}{4}L:6S$	874	0.588	0.279	1.363
No. 23	Concrete	190	12	$1P:1\frac{1}{4}L:6S$	944	0.635	0.302	1.472
No. 33–3	Concrete	161	12	$1P:1\frac{1}{4}L:6S$	1098	0.740	0.351	1.715
					Av. 940	0.633	0.300	1.466
No. 24	Sand-lime No. 1	274	8	$1P:1\frac{1}{4}L:6S$	980	0.207	0.215	0.858
No. 25	Sand-lime No. 1	274	8	$1P:1\frac{1}{4}L:6S$	702	0.148	0.154	0.615
No. 27	Sand-lime No. 1	275	12	$1P:1\frac{1}{4}L:6S$	645	0.136	0.142	0.564
No. 33–1	Sand-lime No. 1	163	12	$1P:1\frac{1}{4}L:6S$	1130	0.238	0.248	0.990
					Av. 864	0.182	0.190	0.757
No. 30	Sand-lime No. 2	221	8	$1P:1\frac{1}{4}L:6S$	830	0.492	0.451	1.794
No. 38	Sand-lime No. 2	69	8	$1P:1\frac{1}{4}L:6S$	709	0.279	0.236	0.838
					Av. 770	0.385	0.343	1.316
No. 17	Eastern surface clay	273	8	$1P:3S$	1075	0.506	0.338	0.898
No. 18	Eastern surface clay	200	8	$1P:3S$	1148	0.460	0.345	1.395
					Av. 1112	0.483	0.341	1.146
No. 19	Eastern surface clay	126	8	$1\frac{1}{4}L:3S$	512	0.241	0.161	0.427
No. 20	Eastern surface clay	409	8	$1\frac{1}{4}L:3S$	719	0.339	0.226	0.600
					Av. 616	0.290	0.194	0.514
No. 33–2	Concrete	162	12	$1L:3S$	500	0.336	0.160	0.780
				4-IN. WALLS				
No. 8	Eastern surface clay	182	4	$1P:1\frac{1}{4}L:6S$	1170	0.469	0.352	1.420
No. 13	Shale	111	4	$1P:1\frac{1}{4}L:6S$	1897	0.288	0.226	0.895
No. 28	Shale	237	4	$1P:1\frac{1}{4}L:6S$	1856	0.282	0.221	0.876
					Av. 1876	0.285	0.224	0.886
No. 28	Concrete	238	4	$1P:1\frac{1}{4}L:6S$	1245	0.838	0.398	1.942

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[a] Ratios represent parts by volume of portland cement, P (94 lb. per cu. ft.) : lime, L (40 lb. per cu. ft.) : loose damp sand, S (78 lb. per cu. ft. of dry contents).

TABLE II.—COMPRESSIVE STRENGTH OF MASONRY—*Continued.*

Sections of walls from 15 to 27 in. in length and from 22 to 40 in. in height.

Test	Kind of Brick	Age of Masonry, days	Nominal Wall Thickness, in.	Mortar[a]	Strength of Masonry, lb. per sq. in.	Ratio of Masonry Strength to Brick Strength		
						Compressive Strength, on edge	Compressive Strength, on side	Modulus of Rupture, flatwise
8 AND 12-IN. HOLLOW (IDEAL ALL ROWLOCK) WALLS								
No. 4	Western surface clay	128	8	$1P:1\frac{1}{4}L:6S$	553	0.255	0.187	0.479
No. 5	Western surface clay	115	8	$1P:1\frac{1}{4}L:6S$	412	0.190	0.139	0.357
No. 6	Western surface clay	124	8	$1P:1\frac{1}{4}L:6S$	395	0.182	0.133	0.342
					Av. 453	0.209	0.153	0.393
No. 11	Eastern surface clay	134	8	$1P:1\frac{1}{4}L:6S$	533	0.213	0.160	0.647
No. 12	Eastern surface clay	232	12	$1P:1\frac{1}{4}L:6S$	632	0.253	0.190	0.768
					Av. 582	0.233	0.175	0.708
No. 16	Shale	316	8	$1P:1\frac{1}{4}L:6S$	1466	0.223	0.175	0.692

[a] Ratios represent parts by volume of portland cement, *P* (94 lb. per cu. ft.); lime, *L* (40 lb. per cu. ft.); loose damp sand, *S* (78 lb. per cu. ft. of dry contents).

for both the solid and the hollow types. The 12-in. walls cracked in nearly the same manner, but the separations were less pronounced. In no case were any well-defined planes of shearing failure formed, failure being preceded or accompanied by cracking and crushing of individual brick.

DISCUSSION OF RESULTS

The results in Table II give both the masonry strength developed and also the ratio of masonry strength to strength of individual brick as tested in compression on edge and on side, and flatwise in bending on 7-in. span under center load. In the diagrams, Figs. 2 to 4, the masonry strengths of 8 and 12-in. solid walls are plotted against the strength of individual brick, and above them the masonry to brick strength ratios against the corresponding brick strengths. Average lines are drawn for clay, shale and sand-lime brick No. 1 only, the concrete and the sand-lime brick No. 2 giving results generally outside of the trend of those for the other kinds of brick named.

It is apparent from the results that there is a general increase in the strength of masonry with increase in the strength of individual brick. This applies for compressive strength of brick tested flatwise and tested on edge and for the transverse strength. If the different kinds of brick had been more nearly similar in structure and surface characteristics, the relation would without doubt have been more consistent. The ratio between strength of masonry and strength of individual brick apparently increases as the brick strength decreases to or below that of the medium grade brick of the A.S.T.M. Standard Specifications for Building Brick (C 21 – 20).[1] For the concrete and soft sand-lime brick tested, this increase of masonry to brick strength ratio is particularly marked. It appears therefore that the strength of the masonry is dependent on other properties than the strength of individual brick and that one of the most probable sources of difference lies in the degree with which bond with the mortar is effected. This would determine the extent to which highly stressed individual brick in the masonry are reinforced by adjacent bricks against bending, shearing and induced tension stresses. The bond with the mortar depends upon the properties of the mortar and surface properties of the brick. Outside of difference in bonding properties of the brick material as such, it is apparent that the degree of

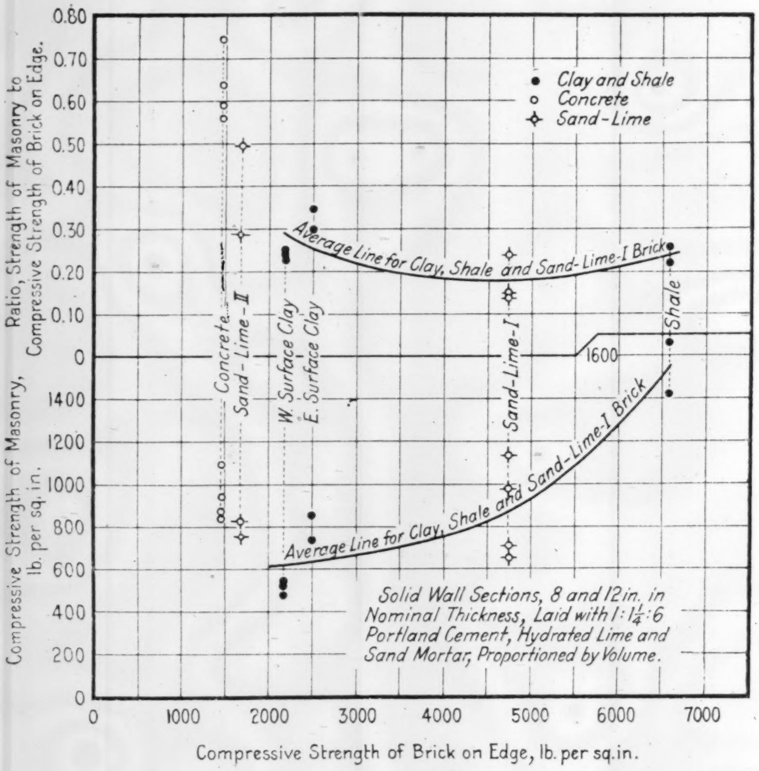

FIG. 2.—Strength of Masonry and Strength of Individual Brick Tested on Edge in Compression.

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[1] 1921 Book of A.S.T.M. Standards.

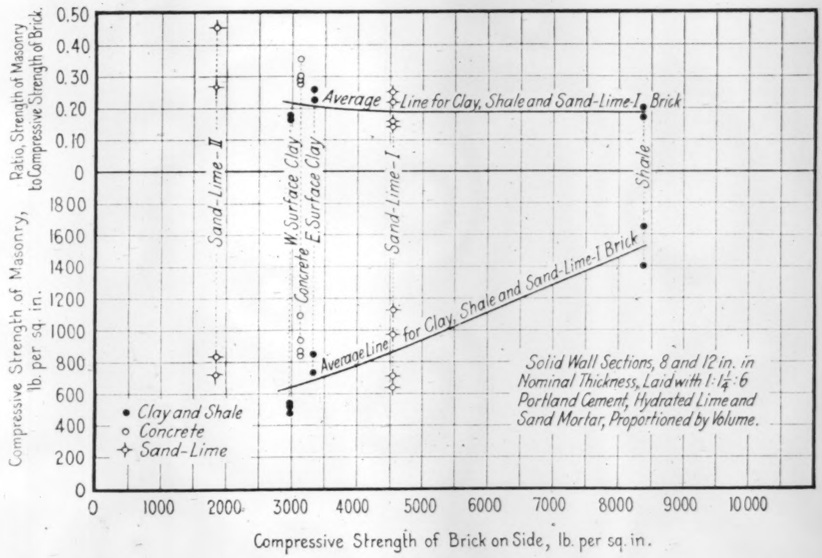

FIG. 3.—Strength of Masonry and Strength of Individual Brick Tested Flatwise in Compression.

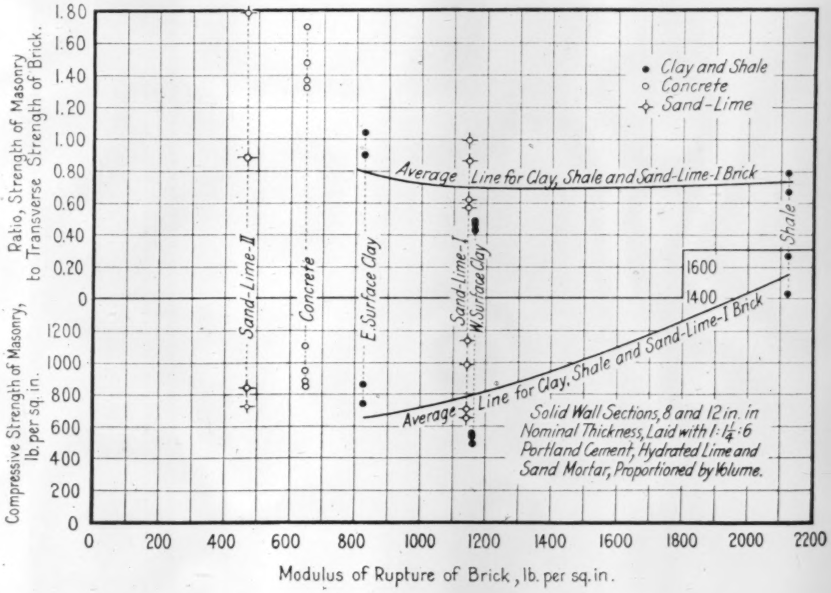

FIG. 4.—Strength of Masonry and Transverse Strength of Individual Brick.

surface roughness is an important factor. Examination of the test results indicate that brick with rough exterior, as caused by the materials used and methods of molding, developed higher relative strengths than smooth hard-surfaced brick. The shale brick, while hard, had rough faces from the cutting wires and maintained a ratio of masonry to brick strength only a little below the average for the surface-clay brick, although the compressive strength of individual brick and of the masonry were about three times larger. The hard sand-lime brick No. 1 developed relatively lower strength in the masonry and had a smooth surface because of fine grinding of material and the high pressures used in molding. Of the two surface-clay bricks, the one with the sanded surface gave relative masonry strengths very nearly 50 per cent higher than the smooth surfaced die-molded brick. The concrete brick had an exceptionally rough surface produced by the method of forming and developed an average masonry strength about 50 per cent above the indicated average for clay brick of comparable strength. The soft sand-lime brick No. 2 in the two tests made also developed high ratios of strength of masonry to strength of brick, that based on compressive strength of brick on side being the highest of any in the given column for the same mortar. It appears that concrete and sand-lime bricks

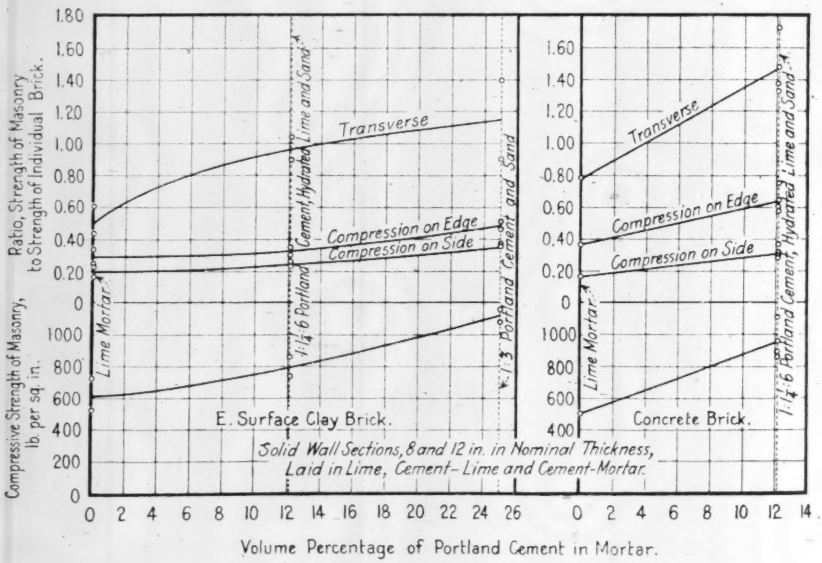

FIG. 5.—Effect of Mortar Proportions on Strength of Masonry.

of low strength have generally rougher surfaces than the stronger brick because of the smaller amount of plastic binder present and consequent greater opportunity for voids to form at the surfaces.

As shown in Fig. 5, there is a consistent gain in strength as the cement content of the mortar is increased, which may be attributed to the reinforcing effect of a stronger mortar bond as previously discussed. For concrete brick, the difference in strength between masonry laid in lime mortar and cement-lime mortar is apparently as large as with clay brick. The average compressive strength of the mortar tested in 2-in. cubes at the age of 60 days was 819, 275 and 61 lb. per sq. in. for the cement, cement-lime, and lime mortars, respectively, the cubes being seasoned in air at room temperatures.

Table III and Fig. 6 give information on the absorption of brick with relation to the strength of the masonry. An increase in the latter with decrease in absorption of the individual brick is to be expected since the brick strength generally increases with decrease in absorption. In the present series the strength-absorption relation was very irregular as between the different kinds of brick, and the fair coincidence of results with the lines of general trend in Fig. 6 cannot be wholly ascribed to this cause. Also, for a given brick strength the absorption of concrete brick is generally lower, and that of sand-lime brick higher, than for clay and shale brick. Upon referring to the first two columns of Table III it is seen that the water content of the clay and shale brick as received was less than 1 per cent and that the absorption of dry clay brick immersed in water was relatively rapid. Concrete and sand-lime brick had a higher water content as received and the rate of absorption of concrete brick was much lower than for clay brick. In the present tests the bricks were laid in the wall as received except that during the months April to September they were sprinkled with water before laying,

TABLE III.—ABSORPTION OF BRICK AND STRENGTH OF MASONRY.

Kind of Brick	Water Content of Brick, per cent		Absorption, per cent, by 5-hour boiling	Average Compressive Strength of 8 and 12-in. Solid Masonry, lb. per sq. in.
	As received	After 5 minutes immersion		
Western surface clay	0.8	9.6	23.1	513
Eastern surface clay	0.9	4.4	15.7	796
Shale	0.3	1.2	6.7	1538
Concrete	5.6	1.3	13.4	940
Sand-lime No. 1	3.1	3.1	16.5	864
Sand-lime No. 2	5.6	6.2	22.6	770

this being the usual practice in this section. The masonry was not sprinkled during the seasoning period as it was thought this would introduce a more favorable condition with respect to fire resistance and strength than often obtains, particularly for interior bearing walls. It is therefore probable that bricks of initial low water content and a high rate of absorption will absorb too much water from the mortar to enable the mortar to attain full strength and the strength of the masonry will be lowered. In Fig. 6, deviation of results from the general trend can also be ascribed to difference in surface properties as discussed above.

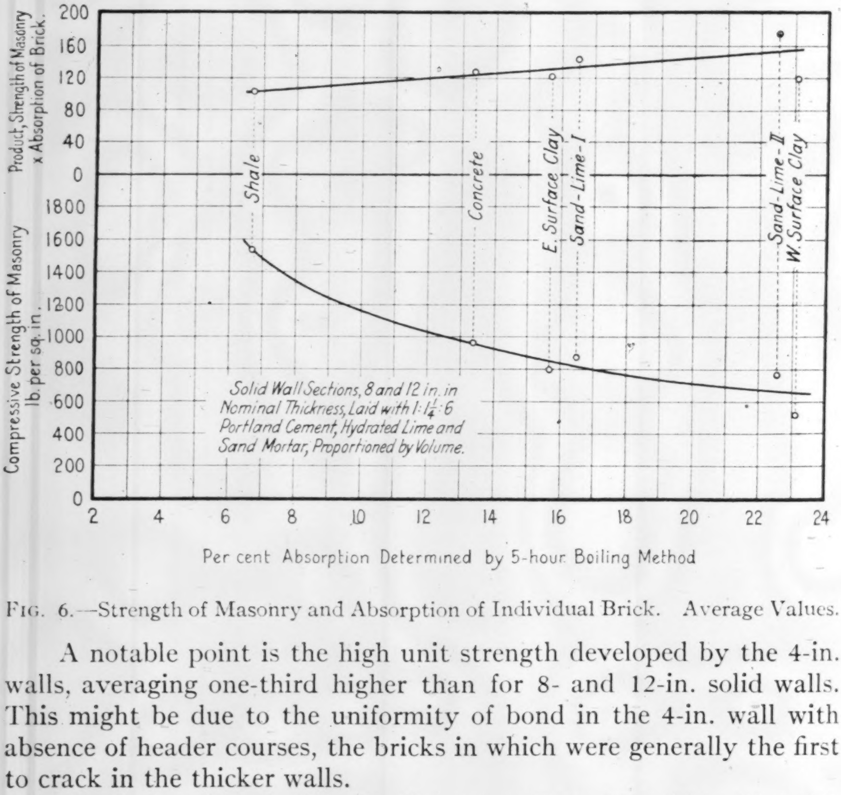

FIG. 6.—Strength of Masonry and Absorption of Individual Brick. Average Values.

A notable point is the high unit strength developed by the 4-in. walls, averaging one-third higher than for 8- and 12-in. solid walls. This might be due to the uniformity of bond in the 4-in. wall with absence of header courses, the bricks in which were generally the first to crack in the thicker walls.

The hollow (Ideal all rowlock) brick wall sections laid with brick on edge developed on the average in these tests a little over 80 per cent of the strength of solid walls of comparable thickness. It should be noted here that in a series of tests of larger brick wall sections recently completed at the U. S. Bureau of Standards the strengths of the hollow and of the solid types were found to be nearly equal. In this latter series the compressive strength of the brick used was higher tested on edge than on side while in the present tests all brick used in hollow walls gave lower results tested on edge than tested flatwise, which may account for the difference found in masonry strength.

Other factors known to influence the strength of the masonry, but not here discussed, are the properties of the mortar materials as they affect the strength and adhesion of the mortar, and the effect of low temperatures on the green masonry. In the present tests the masonry was seasoned at temperatures above freezing, and during the winter months hot water was used for the mortar.

The workmanship on the masonry is a different factor to evaluate. In the present tests a serious effort was made to duplicate average construction conditions, and the character of the masonry and rate at which the work was done indicated that the workmanship was within the range of average performance as it concerns current practice in laying brick. The results, while giving lower ultimate strength values than obtained in previous tests still indicate the presence of factors of safety on allowable working stress values, as defined by building code requirements, of three or more, which is comparable with those obtaining for other building materials of similar variability in properties.

The properties of brick are here discussed only with reference to the resulting strength of the masonry. While within limits this is important, it is not the only consideration involved in determining the essential requirements for building brick. Initial evenness of edges, freedom from chipping and breaking in handling, and ability to withstand weathering conditions may be fully as important for the general conditions governing the use of brick in buildings. In so far as the strength and absorption of brick give indication of ability to meet these requirements, consideration need be given them in fixing specification limits.

Acknowledgment.—Acknowledgments are due to Messrs. H. E. Newcomer, L. M. Hammond and B. Schlosser, of the Bureau of Standards, by whom the tests of brick and masonry were made, and to Mr. F. E. Schmitt, Associate Editor of the *Engineering News-Record*, at whose suggestion the paper was modified to include consideration of absorption of brick in relation to strength of masonry.

FURTHER STUDY OF ACCELERATED WEATHERING: EFFECT OF VARIATIONS IN EXPOSURE CYCLE COMBINATIONS ON COMMON TYPES OF VARNISHES[1]

By H. A. Nelson[2] and F. C. Schmutz[2]

Experience has proved that variations in climatic conditions have profound influences on the life of paint and varnish films. Previous work[3] on the problem of accelerated weathering has also shown the importance of the climatic cycle. It is the aim of this investigation to determine, in so far as practicable with the means at hand (1) the relative deteriorating effectiveness of the most common of the many possible combinations of weathering agents (light, heat, moisture, etc.) and (2) to study the results of variations in the order and frequency of these weathering agents in the exposure cycle.

Such an investigation naturally divides itself into two parts: (1) examination of varnish finishes, and (2) examination of paint surfaces. The former was selected as a starting point and constitutes the subject of this paper. This was done because varnishes, in one form or another, essentially represent the organic materials used as binders in paint products. Thus, results observed in the study of varnishes should aid in the interpretation of results obtained in a study of pigmented mixtures. Then again, since the deterioration of varnished surfaces is quite graphic, these results are more readily obtained and recorded for interpretation.

Experimental Procedure

Varnishes Tested.[4]—The choice of varnishes was made with two objects in mind: (1) to cover various types of varnishes classified according to their use, as furniture finishing, interior trim, universal varnish and so forth; (2) to include varnishes made from a variety of raw materials. The varnishes are listed in Table I.

Of course, there are many additional representative varnishes that could have been selected, but because of the limitations of the apparatus, the choice was made quite general. Besides, the reader should note particularly that it is not the primary object of this work to check up the relative merits of these varnishes. Certain comparisons will inevitably follow and these are briefly discussed later, but the samples were not selected with this object in view.

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[1] A contribution from the Research Laboratories of The New Jersey Zinc Co.

[2] Investigator, Paint Section, Research Division, New Jersey Zinc Co., Palmerton, Pa.

[3] H. A. Nelson, "Accelerated Weathering of Paints on Wood and Metal Surfaces," *Proceedings*, Am. Soc. Testing Mats., Vol. 22, Part II, p. 485 (1922).

[4] We are indebted to The Lowe Brothers Co., Dayton, Ohio, for furnishing these experimental varnishes, and to Mr. E. W. Fasig of that company for valuable cooperation in suggesting the types of varnishes.

Offhand, there might also be some inclination to question the value of information derived from exposing short oil varnishes, intended for interior use only, to an outdoor exposure cycle until we consider that these contain the same basic materials as other varnishes, the differences being largely in the proportions of the basic materials.

TABLE I.—EXPERIMENTAL VARNISHES.

Varnish	Classification	Gum	Length in Oil[1]		Volatile, per cent[2]	Kauri Reduction,[3] per cent Determined by Laboratory No.			
			Tung Oil	Linseed Oil		1	2	3	4
No. 1..	Mixing..............	Limed Rosin...........	7	10	....	....	....	..	..
No. 2..	Rubbing............	50 per cent Limed Rosin 50 per cent Congo......	10	none	....	..	..	..	..
No. 3..	Rubbing............	50 per cent Kauri...... 50 per cent Ester.......	1	5	....	..	..	..	..
No. 4..	Grinding..............	No. 1 Kauri............	none	25	48.7	90–100	95	75–80	90–100
No. 5..	Automobile Finishing	50 per cent Ester...... 50 per cent Congo......	14	35	37.1	80–90	98	50–55	Slat 80
No. 6..	Mixing..............	Limed Rosin............	72	28	65.1	120–130	100–105	100–105	120–130
No. 7..	Mixing..............	Ester..................	36	none	51.3	90–100	89	90–95	100–90

[1] By length of oil is meant the number of gallons of oil per 100 lb. of gum. Kettle losses are not accounted for.

[2] Figure given is average for four laboratories. Maximum deviation from average was 2 per cent.

[3] By A.S.T.M. methods appearing in the Tentative Methods of Testing Oleo-Resinous Varnishes (D 154 - 23 T), *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part I, p. 655 (1923). Laboratory No. 1, New Jersey Zinc Co.; No. 2, Lowe Bros.; No. 3, U. S. Bureau of Standards; No. 4, H. A. Gardner.

Such varnishes were deliberately chosen with the hope that a study of their deterioration would yield additional information.

Preparation of Panels.—All panels used were 6 by 12 in., No. 22-gage black iron. After a thorough cleaning, these were coated by dipping with two coats of a black baking undercoater, which was a highly water-resistant enamel with a tung oil - ester gum vehicle. The first coat was baked four hours at about 80° C., and the second coat six hours at about 75° C.

Two sets of test panels were prepared. On the first set the varnishes were brushed on in two coats, except the automobile finishing varnish, which was applied in one coat only. The second set was prepared by applying one coat by dipping.

No essential difference appeared between the results on the brush and dip sets, and, since the method of application did not have any noticeable influence, the results from both sets have been considered as one.

Selection of Exposure Cycles.—The factors involved in any exposure cycle can be generally classified as (1) light, with heat as its accompanying auxiliary; (2) heat alone; (3) moisture, both as water and water vapor; and (4) temperature changes. Obviously, it was impractical to attempt to cover every probable combination of these factors. For reasons that will be discussed later, heat (by itself) and humidity changes were those chosen for elimination as variables. The temperature in the light tank was maintained at 40° C. with a relative humidity of 50 per cent.

TABLE II.—EXPOSURE CYCLES USED.

Cycle No.	Weathering Agent	Length of Exposure Period Under Each Agent	Comments
1	Light	Continuous	Panel temperature constant at 40° C. while under exposure.
2	Water	Continuous	
3	Refrigeration	Continuous	
4	Water—Light	3 hr.	
5	Light—Refrigeration	3 "	
6	Water—Refrigeration	3 "	
7	Water—Light	18 hr.	
8	Light—Refrigeration	18 "	
9	Water—Refrigeration	18 "	
10	Light—Water—Refrigeration	3 hr.	The sequences of any two of the three weathering factors are used in all possible combinations.
11	Light—Water—Refrigeration	9 "	
12	Light—Water—Refrigeration	18 "	
13	Out-door Test Fence Exposure		

With light, water and temperature changes (refrigeration) considered as deteriorating agents, the final selection of cycles was made with a view of covering as many conditions and combinations as practicable. First, it was essential to determine the effect of each weathering factor alone, as continuous light, continuous water and continuous refrigeration. Next, combinations of two of these with long and short exposure times were decided upon. Third, cycles involving the use of all three, with three different exposure times, were selected; the sequences of any two of the three weathering factors were in all possible combinations. Finally, a comparative outdoor exposure was started.

A summary of the cycles used is given in Table II. The duration of exposure to each controlled destructive agent was such as to represent approximately many, medium, and few weather changes in outdoor exposure conditions.

Recording of Results.—The first photograph was taken soon after the first cracking had developed. In a few cases, the first cracking was so faint that dusting with magnesium carbonate had to be resorted to before photographing. Photographs were then taken every other day for about six days after the first cracking, and about once a week thereafter until the end of the experiment. In some cases, with the long oil varnishes, the deterioration did not develop as cracking, but only as a general weathering of the surface, which could not be recorded by ordinary photographs. In a few representative cases, microphotographs were resorted to.

In addition, a record was kept of the reduction in gloss, which was determined by means of the Ingersoll "Glarimeter,"[1] an instrument originally developed for the paper industry. This instrument does not pick up the fine distinctions in gloss which are visible to the eye, but, generally, it served the purpose for these experiments. It gives an arbitrary reading on a scale ranging from 10 to 60, and all results are recorded on this arbitrary scale. Since the ground color in all cases was the same, these readings were comparable.

APPARATUS

For detailed description of the apparatus, the reader is referred to papers by one of the authors.[1] Each of the three weathering exposures, light, water, and refrigeration, is now being carried out in a separate unit.

Light.—The source of light is the 30-in. quartz mercury arc, as described in the previous papers referred to.[2] Complete air circulation is maintained, which prevents any accumulation of ozone. Special precautions have been taken so as to prevent a direct draft of air on the test panels. As stated before, a relative humidity of 50 per cent with a temperature of 40° C. was maintained during these experiments.

Water.—The water is now distributed from the top of the tank by means of an ordinary lawn spray inverted. By adjusting the side arms, an even distribution of water can be maintained over all the panels.

Refrigeration.—The temperature change involved a rapid cooling of the test panel and maintaining it at a temperature of $-13°$ C.

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[1] *Journal*, Optical Society of America, Vol. 5, p. 213 (May, 1921); *Electrical World*, Vol. 63, pp. 645–647 (March, 1914).

[2] H. A. Nelson, "Accelerated Weathering of Paints on Wood and Metal Surfaces," *Proceedings*, Am. Soc. Testing Mats., Vol. 22, Part II, p. 485 (1922); also, Report of Second Annual Meeting of Chemists of Paint and Varnish Industry (June, 1923), Paint Manufacturers Assoc., *Circular No. 184*, p. 294.

Since the refrigerating unit is automatically controlled, the variation in temperature is not more than about 1° C. either way.

ACCELERATED TESTS OF VARNISH NO. 1

The progress of the deterioration and the final results have been summarized in Table III and in Fig. 1. The panel from the continuous refrigeration exposure was omitted from the figure, since it did not show any definite cracking.

TABLE III.—SUMMARY OF OBSERVATIONS ON VARNISH NO. 1.

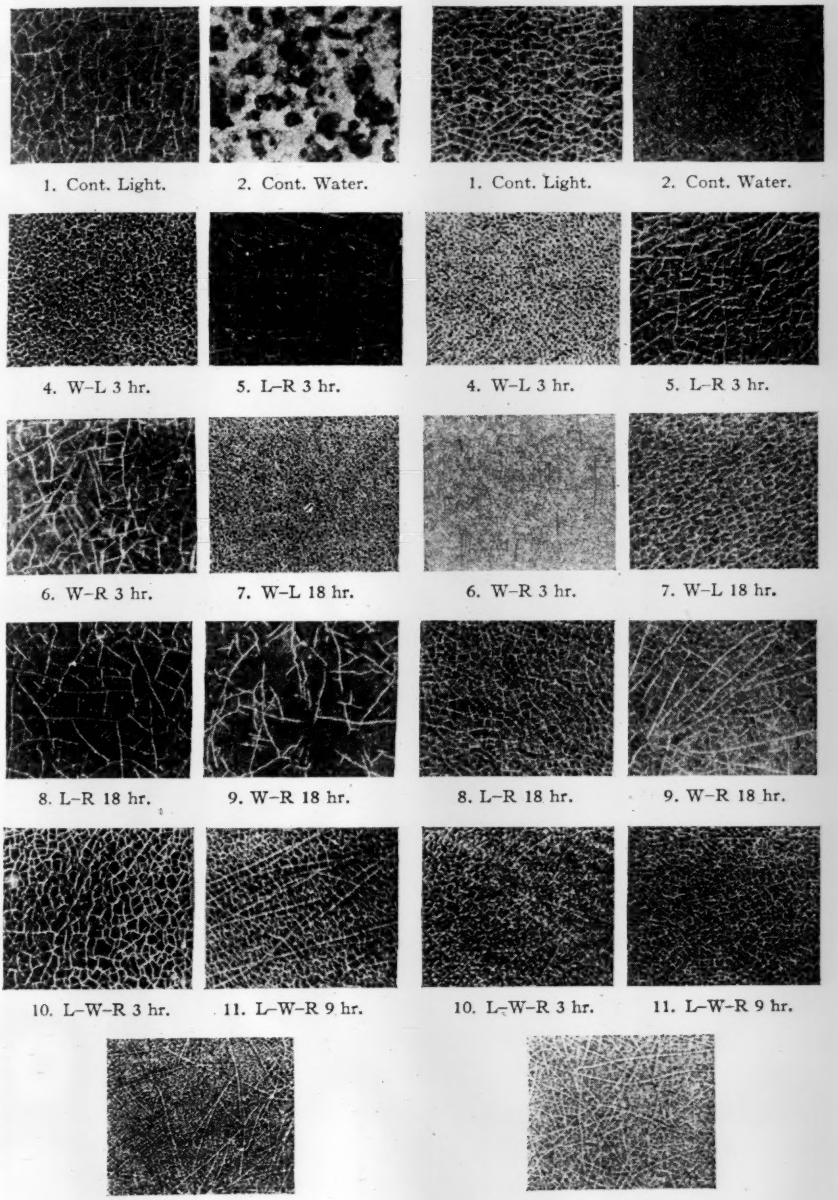
Gum: Limed Rosin. Oil: 7 gal. Tung and 10 gal. Linseed per 100 lb. of gum. (See Table I.)

Cycle No.	Weathering Agents[1]	Exposure Period	Development of Deterioration	Final Condition after 24 Days' Exposure	Decrease in "Glarimeter" Reading
1	L	Continuous	Slight cracking 90 hr. Marked cracking 126 "	Very badly cracked; no permanent whitening	4.8
2	W	Continuous	Blue cast 54 " Definite cracking 144 "	General deterioration; bad permanent whitening	4.1
3	R	Continuous	Minute crazing 180 " Definite cracking none	Very slightly crazed	1.5
4	W-L	3 hr.	Bad cracking 12 "	General deterioration; very slight permanent whitening	15.8
5	L-R	3 "	Slight cracking 15 " Marked cracking 108 "	Very badly cracked; no permanent whitening	3.3
6	W-R	3 "	Blue cast 15 " Fine cracking 24 "	Very badly cracked; no permanent whitening	9.8
7	W-L	18 "	Blue cast 54 " General surface deterioration 72 "	General deterioration; very badly whitened	16.8
8	L-R	18 "	Badly cracked 144 "	Very badly cracked; no permanent whitening	9.3
9	W-R	18 "	Blue cast 108 " Badly cracked 54 "	Very badly cracked; no permanent whitening	4.8
10	L-W-R	3 "	Water spotting 18 " Bad cracking 15 "	General deterioration; no permanent whitening	14.0
11	L-W-R	9 "	Blue cast Bad cracking } 36 "	Very badly cracked; slight permanent whitening	15.5
12	L-W-R	18 "	Blue cast 72 " Fine cracking 72 "	Very badly cracked; considerable permanent whitening	22.8

[1] L = Light; W = Water; R = Refrigeration.

Discussion of the Results. Continuous Light.—The principal effect of light alone on varnish No. 1 is a deadening of the film with a complete elimination of distensibility. The film cannot then take up the stress induced by shrinkage or even slight temperature changes, and soon breaks up with an angular type of cracking. See cycle 1, Fig. 1.

Continuous Water.—The first effect is the formation of an emulsion of water and varnish over the surface, developing a light blue cast. The continued wetting causes a deadening action, though



1. Cont. Light. 2. Cont. Water. 1. Cont. Light. 2. Cont. Water.

4. W–L 3 hr. 5. L–R 3 hr. 4. W–L 3 hr. 5. L–R 3 hr.

6. W–R 3 hr. 7. W–L 18 hr. 6. W–R 3 hr. 7. W–L 18 hr.

8. L–R 18 hr. 9. W–R 18 hr. 8. L–R 18 hr. 9. W–R 18 hr.

10. L–W–R 3 hr. 11. L–W–R 9 hr. 10. L–W–R 3 hr. 11. L–W–R 9 hr.

12. L–W–R 18 hr. 12. L–W–R 18 hr.

(*a*) Early Deterioration. (*b*) Final Condition.

FIG. 1.—Typical Deteriorations of Varnish No. 1 in Accelerated Weathering (**Actual Size**).

much slower than that of light, which shows up only on drying. The film finally loses so much of its inherent distensibility that even a slight drying or temperature change, as during observation periods, results in cracking. As the varnish dries, the water in the water-varnish emulsion is replaced by air, causing a permanent whitening. It is the continued existence of this emulsion, either as water and varnish, or as air and varnish, that somewhat modifies the angular cracking under the continuous water exposure. See cycle 2, Fig. 1.

Continuous Refrigeration.—Apparently, refrigeration alone has little effect on this varnish. There is very little fall in gloss and only a very faint cracking, probably resulting from a slight deadening of the film surface due to normal air oxidation. No definite cracking has been obtained.

Water-Light Combination.—As stated before, water forms a water-varnish emulsion on the surface. If this is then subjected to light, each particle of water in the emulsion probably acts as a focusing lens and increases the deteriorating action on the varnish below. Thus, we have an intensified light action at an infinite number of localized points, in addition to the normal light action due to the presence of absorbed water. As the film is partially dried out by the heat from the light, this intensified action decreases and the slower deterioration by the light alone, in the presence of the remaining absorbed moisture, continues. If, however, the film is kept excessively moist because of very high humidity while under the light, or because of frequent changes from water to light, this intensified localized deterioration becomes more nearly continuous. This accounts for the greater effectiveness of the water-light combination under the three-hour changes. See cycle 4, Fig. 1.

Because of the localized activity of the light, this combination has a granular, pebbly type of deterioration, as may be readily recognized in cycles 4 and 7, Fig. 1. When the combination is modified by the introduction of temperature changes, the pebbly deterioration still continues, although somewhat modified by another type of cracking. This is exemplified by cycle 12, Fig. 1. The latter effect will be considered later.

Temperature Changes.—As indicated in the previous results, continued refrigeration, alone, has very little effect on varnish No. 1. On the other hand, if the film has decreased in distensibility due to light or water action, the change to the refrigeration temperature causes stresses which result in cracking. As may be noted in the cycles involving refrigeration, especially those not including light, as cycles 6 and 9, Fig. 1, the angle at which the cracks meet each other is often 120 deg., representing a vertex of stresses and strains. Thus, the introduction of a temperature change brings about a straight-line, angular type of cracking. The minuteness of this type of cracking depends upon the amount of reduction in the distensibility of the film between temperature changes.

Reduction of Gloss.—The pebbly surface deterioration due to light and water, and the angular cracking due to temperature changes, or a combination of both, bring about the drop in gloss. The more finely the surface is disintegrated in either case, the greater will be the dulling. Then again, combinations of the two types of deterioration act additively toward giving the greatest drop in gloss.

Light-Refrigeration Combination.—The first cracking under both exposure times was very similar, as indicated by cycles 5 and 8, Fig. 1 (*a*). According to the experimental data, frequency of temperature changes is more effective in producing first cracking. On the other hand, the long light exposures, followed by temperature changes, are more effective in producing the fine ultimate deterioration. This is due to the great decrease in distensibility between temperature changes, and the especially high stresses occurring at the change period. This also accounts for the greater dulling with the light-refrigeration cycle under long light exposures with few changes.

Water-Refrigeration Combination.—This cycle introduces a new destructive result of temperature changes, namely, the change of phase of the water emulsion in the film. The expansion due to this action sets up an infinite number of stresses within the film, besides those normally introduced by the temperature change itself. As may be seen from cycles 6 and 9, Fig. 1 (*a*), the angular cracking meeting at 120-deg. vertices is quite evident. Since this stress-strain effect takes place at every refrigeration period, naturally the first cracking and the greatest deterioration will occur under the short-exposure, many-change cycle. Because of the expansion and change in phase of the water, the emulsion formed apparently is broken up each time by internal cracking. Thus, there is no permanent whitening under a water-refrigeration exposure.

Inasmuch as the deadening of the film by the water soaking proceeds very slowly in the absence of light, the effect of this water-refrigeration combination, by itself, is not as destructive as might be supposed.

Light-Water-Refrigeration Combinations.—The effect of the length of exposure under each weathering factor and the frequency of the changes play an important part in the completed cycle. The data in Table III and photographs of cycles 10, 11 and 12 in Fig. 1 clearly verify these facts.

In the frequent-change cycle, the major deteriorating force of varnish No. 1 is, undoubtedly, the ultra-violet light focused through the water which accumulates at each wetting of the film. This accounts for the predominance of the pebbly type of deterioration, although, due to the frequent temperature changes, some angular cracking is present. See cycle 10, Fig. 1 (*b*). In the cycle involving long exposure periods with few changes, the amount of deadening of the film between temperature variations is considerable; hence, the effectiveness of the light-refrigeration combination is greatly increased.

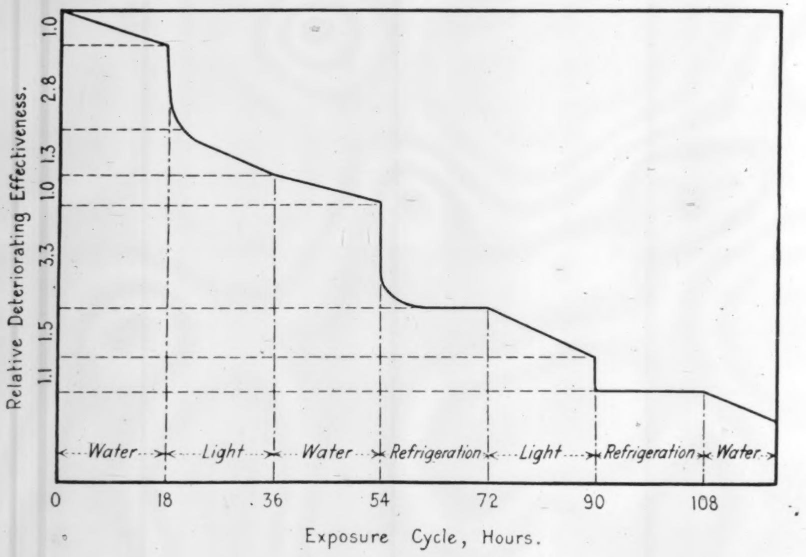


FIG. 2.—Graphic Representation of Deterioration of Varnish No. 1.

The values given for "Relative Deteriorating Effectiveness" of the various weathering factors, and their combinations, were arbitrarily determined from the length of time required to produce cracking in cycles containing 18-hour exposure periods, and from the total reduction in gloss under these cycles, as measured by the "Glarimeter." The least effective factor was considered as unity, and the remainder as multiples of this.

This accounts for the predominance of the straight-line type of cracking, although the pebbly deterioration is also present in considerable amounts. See cycle 12, Fig. 1 (*b*). On account of the long water-light exposures in cycle 12, the final air-varnish emulsion penetrates to a considerable depth. Subsequent wetting probably displaces the air only in that portion of the emulsion near the surface, while the air-varnish emulsion below remains undisturbed. If the water-refrigeration action is more frequently repeated, more of the original air-varnish emulsion is destroyed. As a result, we have less whitening in cycle 10 than in cycle 12, and the most whitening in cycle 7 (water-light alone).

A graphic representation of what might be taking place in a cycle composed of 18-hour exposures under light, water and refrigeration has been attempted in Fig. 2. The basic effects are very similar in all the cycles; the cycle referred tow as selected only as an example No intrinsic values are available at present, but relative values have been approximately calculated from the data and observations. Referring to Fig. 2, there is first a deadening action due to continued water soaking. Next, the intensified action of the light takes place, continuing as long as the film remains saturated. As drying proceeds, this effect decreases in intensity until the moisture in the film reaches equilibrium with the atmosphere in the tank. Then the deterioration due to light, under the adopted conditions, continues for the balance of the 18 hours. This is followed by the slower action of the subsequent 18 hours of water. Next, the comparatively rapid action of the temperature change below the freezing point takes place. After being brought down to the lowest temperature, and the film reaches a state of equilibrium, no further deterioration takes place during the remainder of the refrigeration period. The subsequent light period considerably reduces the distensibility of the film, and at the next temperature change, deterioration due to the induced stresses ensues. Repeating this cycle completes all the possible sequences of any two of the three weathering factors.

Conclusions for Varnish No. 1.—Because of lack of water-resistant properties and distensibility in this type of varnish, the following weathering effects seem to cause the severest deterioration:

1. Repeated soaking of the film followed by short light exposures, or wetting while under the light;
2. Long light exposures followed by rapid cooling and short refrigeration periods;
3. Repeated saturation followed by rapid cooling and short refrigeration periods.

ACCELERATED TESTS OF VARNISH NO. 2

The progress of the deterioration and the final results have been summarized in Table IV and in Fig. 3. The panel from the continuous refrigeration exposure was omitted from Fig. 3 since it did not show any definite cracking.

Discussion of Results.—As may be noted from the data, Table IV, in no case was there any permanent whitening or even any temporary blueing due to the water exposure. Although the gum content included

50 per cent limed-rosin and the oil content was low, this varnish was quite impervious to the emulsifying action of water. But this does not mean, as we shall see later, that the film was especially resistant to the deadening action of the water exposure.

As might be expected, with a varnish of this composition, the major cause of the breaking down of the film was its low distensibility. Fig. 3 shows that, even in those exposures which finally acquired a general deterioration of a granular nature, the disintegration started with a straight-line cracking. The slight original distensibility of this varnish is almost destroyed by continuous exposure to either light or water. It follows that any slight unavoidable temperature variation incident to the observation periods, develops stresses which cause cracking. Continuous light exposure resulted in cracking in 126 hours, and continuous water in 108 hours. These results indicate that even though this varnish may be fairly resistant to the emulsifying action of water, it apparently is not resistant to the deadening induced by saturation. No doubt there is some absorption of moisture during the water exposures, which causes an intensified light activity

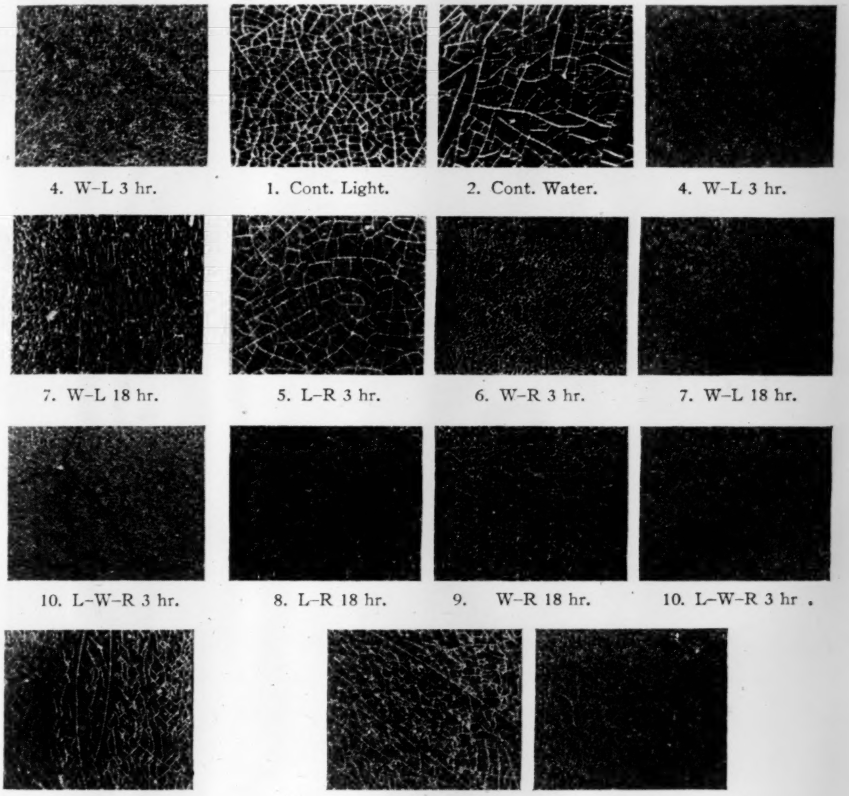
TABLE IV.—SUMMARY OF OBSERVATIONS ON VARNISH NO. 2.

Gum: Limed Rosin and Congo. Oil: 10 gal. Tung per 100 lb. of gum. (See Table I.)

Cycle No.	Weathering Agents[1]	Exposure Period	Development of Deterioration	Final Condition after 24 Days' Exposure	Decrease in "Glarimeter" Reading
1	L	Continuous	Bad cracking........... 126 hr.	Slightly dulled and badly cracked...	1.0
2	W	Continuous	Bad cracking.......... 108 "	Good gloss, but badly cracked......	0.0
3	R	Continuous	No definite cracking. Slight minute crazing 144 "	Good condition....................	0.0
4	W-L	3 hr.	Minute cracking........ 12 " Bad cracking........... 27 "	Generally deteriorated with considerable dulling..................	19.2
5	L-R	3 "	Bad cracking........... 42 "	Slightly dulled and badly cracked...	1.0
6	R-W	3 "	Minute cracking........ 54 " Bad cracking........... 66 "	Good gloss, but badly cracked......	0.0
7	W-L	18 "	Bad cracking........... 54 "	Generally deteriorated with considerable dulling................	11.5
8	L-R	18 "	Bad cracking.......... 144 "	Slightly dulled and badly cracked..	2.0
9	R-W	18 "	Bad cracking........... 90 "	Good gloss, but badly cracked......	0.0
10	L-W-R	3 "	Bad cracking........... 24 "	Generally deteriorated with considerable dulling................	12.4
11	L-W-R	9 "	Bad cracking........... 36 "	Generally deteriorated with considerable dulling and some angular cracking....................	6.0
12	L-W-R	18 "	Bad cracking........... 90 "	Generally deteriorated with considerable dulling and some angular cracking......................	7.0

[1] L = Light; W = Water; R = Refrigeration.

in the water-light change, just as in the case of varnish No. 1. The deadening action of the water and the light, coupled with the intensified activity at the change period, explains the greater destructive action of the water-light combination. See Table IV, cycle 4. For the reasons discussed under varnish No. 1, many changes (with the frequent wetting) is here also the more severe exposure in this combination. See cycles 4 and 7, Fig. 3.



4. W–L 3 hr. 1. Cont. Light. 2. Cont. Water. 4. W–L 3 hr.

7. W–L 18 hr. 5. L–R 3 hr. 6. W–R 3 hr. 7. W–L 18 hr.

10. L–W–R 3 hr. 8. L–R 18 hr. 9. W–R 18 hr. 10. L–W–R 3 hr.

12. L–W–R 18 hr. 11. L–W–R 9 hr. 12. L–W–R 18 hr.

(*a*) Early Deterioration. (*b*) Final Condition.

FIG. 3.—Typical Deteriorations of Varnish No. 2 in Accelerated Weathering (Actual Size).

In this case also, long light exposures followed by a temperature change cause very fine surface cracking and a greater drop in gloss than does the frequent change cycle with short exposures. See cycles 5 and 8, Table IV and Fig. 3.

In cycles involving the three weathering agents, frequent changes with short exposure periods cause a fine granular deterioration of the surface due to the increased activity of the water-light combination. This latter effect, coupled with the increased destructiveness of a water-refrigeration combination, makes cycle 10 the severest of cycles 10, 11 and 12. On the other hand, few changes and long exposure periods increase the intensity of the light-refrigeration combination, causing a fine surface cracking. See cycle 12, Fig. 3. In the intermediate nine-hour exposure, the severity of both the frequent-change water-light combination, and the long-exposure light-refrigeration combination, are missing. Thus, the disintegration is a rather coarse angular cracking. See cycle 11, Fig. 3. It follows that the reduction in gloss in this cycle is least of the three cycles 10, 11 and 12.

TABLE V.—SUMMARY OF OBSERVATIONS ON VARNISH NO. 3.

Gum: Kauri and Ester. Oil: 1 gal. Tung and 5 gal. Linseed per 100 lb. of gum. (See Table I.)

Cycle No.	Weathering Agents[1]	Exposure Period	Development of Deterioration	Final Condition after 24 Days' Exposure	Decrease in "Glarimeter" Reading[2]
1	L	Continuous	Bad cracking.......... 126 hr.	Coarse, large cracking............	....
2	W	Continuous	Slight pitting.......... 90 " Only increased pitting, no definite cracking.. 486 "	No definite cracking; some pitting..	....
3	R	Continuous	Minute crazing; but no definite cracking..... 144 "	Minute crazing; no definite cracking	....
4	W-L	3 hr.	Bad cracking.......... 30 "	Completely cracked..............	....
5	L-R	3 "	Minute crazing.......... 15 " Definite cracking....... 27 "	Completely cracked..............	....
6	W-R	3 "	Minute crazing........ 72 " Slight cracking......... 90 "	Only slightly cracked.............	....
7	W-L	18 "	Fine cracking.......... 72 " Bad cracking .... 108 "	Completely cracked; also a slight bloom........................	....
8	L-R	18 "	Fine cracking.......... 108 " Bad cracking.......... 144 "	Completely cracked..............	....
9	W-R	18 "	Minute crazing........ 216 " Slight cracking......... 488 "	Only slightly cracked.............	....
10	L-W-R	3 "	Bad cracking.......... 36 "	Completely cracked	....
11	L-W-R	9 "	Bad cracking.......... 45 "	Completely cracked..............	....
12	L-W-R	18 "	Bad cracking.......... 90 "	Completely cracked..............	....

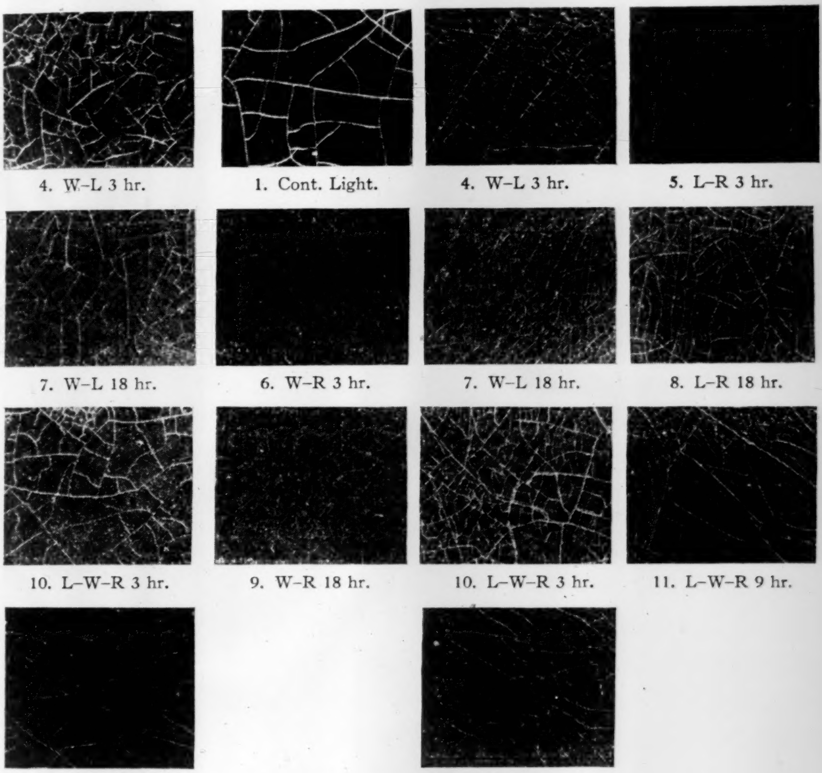
[1] L = Light; W = Water; R = Refrigeration.
[2] Practically no reduction in gloss was noted under any of the cycles.

Conclusions for Varnish No. 2.—The previous discussion indicates that the following factors seem to have the greatest disintegrating effect on this type of varnish:

1. Temperature variations, especially those crossing the freezing point of water;
2. Short exposures to water, followed by light.

ACCELERATED TESTS OF VARNISH NO. 3

The progress of the deterioration and the final results have been summarized in Table V and in Fig. 4. Because of the absence of definite cracking, the panels exposed under continuous water and continuous refrigeration have been omitted from this figure.



4. W–L 3 hr. 1. Cont. Light. 4. W–L 3 hr. 5. L–R 3 hr.

7. W–L 18 hr. 6. W–R 3 hr. 7. W–L 18 hr. 8. L–R 18 hr.

10. L–W–R 3 hr. 9. W–R 18 hr. 10. L–W–R 3 hr. 11. L–W–R 9 hr.

12. L–W–R 18 hr. 12. L–W–R 18 hr.

(*a*) Early Deterioration. (*b*) Final Condition.

FIG. 4.—Typical Deteriorations of Varnish No. 3 in Accelerated Weathering (Actual Size).

Discussion.—Because of the comparatively low oil and high hard gum content, this varnish had very little distensibility. The results show a high resistance to water; in fact, there was much less indication of surface absorption than with varnish No. 2. Thus, the first breakdown in all cases where disintegration occurred was a stress-strain cracking due to the temperature variations. Frequent changes from the warm light tank to the refrigerator caused the earliest cracking.

The ultimate deterioration was worst on those panels which included a water-light exposure in the cycle. After first cracking, the water apparently becomes incased in the newly developed openings, and as a result, in subsequent light exposures, causes intensified light effects, which persist until these minute cracks dry out. This accounts for the more severe and finely disintegrated ultimate condition of those panels exposed to cycles containing water-light combinations.

Because there was neither an emulsifying action nor a surface softening due to excessive water, the disintegration under the water-light, or water-refrigeration changes was not as fine and infinitely distributed as with the previous varnishes. This fact accounts for the negligible drop in gloss.

TABLE VI.—SUMMARY OF OBSERVATIONS ON VARNISH NO. 4.

Gum: No. 1 Kauri. Oil: 25 gal. Linseed per 100 lb of gum. (See Table I.)

Cycle No	Weathering Agents[1]	Exposure Period	Development of Deterioration	Final Condition after 35 Days' Exposure	Decrease in "Glarimeter" Reading
1	L	Continuous	Badly dulled............. 375 hr.	Badly dulled, with noticeable general deterioration............	4.0
2	W	Continuous	Slight pitting and softening 108 "	Generally pitted; also a slight bloom....................	0.0
3	R	Continuous	....	Good condition................	0.0
4	W-L	3 hr.	Very fine cracking........ 423 "	Considerable cracking and dulling	2.0
5	L-R	3 "	Noticeable general deterioration................ 666 "	Noticeable general deterioration..	2.5
6	W-R	3 "	....	Good condition................	0.0
7	W-L	18 "	Slight cracking........... 702 "	Considerable angular cracking....	1.3
8	L-R	18 "	Minute seed cracking..... 378 " Definite cracking......... 486 "	Minute cracking and general deterioration................	3.0
9	W-R	18 "	....	....	0.0
10	L-W-R	3	Slight cracking.......... 540 "	Badly cracked..................	2.0
11	L-W-R	9 "	Slight cracking........... 691 "	Badly cracked..................	1.0
12	L-W-R	18 "	Slight cracking........... 691 "	Badly cracked..................	1.0

[1] L = Light; W = Water; R = Refrigeration.

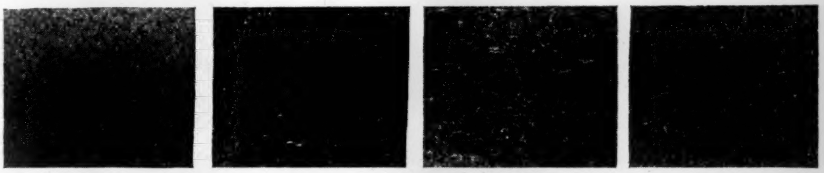
Long exposures under water and light caused a slight bloom on this varnish. No definite reason for this effect can be deduced from the data, since neither continuous light nor water produced this result.

Conclusion for Varnish No. 3.—This varnish has a low resistance to the effect of temperature changes. The deadening action of light intensifies the effect of the temperature changes. It is only after cracking has begun that water causes any visible disintegration, since this varnish appears to be inherently water resistant.

ACCELERATED TESTS OF VARNISH NO. 4

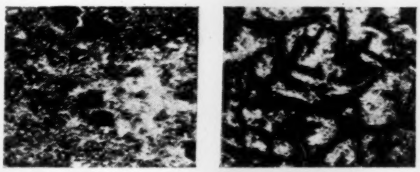
The progress of deterioration and the final results have been summarized in Table VI and in Fig. 5.

Discussion.—This varnish, being longer in oil than any of those previously discussed, was quite distensible. Since linseed oil, which constituted the entire oil content, does not oxidize to an especially water-resistant film, the action of water was quite severe. Probably, because the gum was a hard, quite water-resisting variety, there was no permanent whitening, but the general effect was a softening of the film which rendered it quite mushy and sensitive to finger markings.


4. W–L 3 hr. 7. W–L 18 hr. 10. L–W–R 3 hr. 12. L–W–R 18 hr.

Final Condition.

FIG. 5.—Typical Deteriorations of Varnish No. 4 in Accelerated Weathering (Actual Size).


5. L–R 3 hr. 8. L–R 18 hr.

Final Condition.

FIG. 6.—Photomicrographs of Varnish No. 4 in Accelerated Weathering (×150).

No doubt considerable water was absorbed by this film, and, in subsequent light exposures, the intensified action of light due to the presence of moisture is quite marked. Because of the original distensibility of the film, more time was required to complete the deadening action. An angular cracking type of deterioration developed on the dry film. Water-to-light changes naturally produced the greater deadening and ultimate deterioration. See cycles 4 and 7, Fig. 5.

In a light-refrigeration combination, the severity of the temperature change, coupled with the great decrease in surface distensibility after a long light exposure, readily induced fine surface cracking. In a similar cycle with short exposure periods and frequent changes, the deadening between temperature changes had not progressed far enough to cause actual cracking; rather it seems to have resulted in a surface chipping (or flaking) action which accounts for the dull and deteriorated appearance of this panel. Comparison of the photomicrographs of cycles 5 and 8, Fig. 6, illustrates these distinctly different types of failure. In a cycle involving frequent changes and all the weathering agents, the intensified deadening action of the water-light combination accounts for the earlier cracking, while the chipping (or flaking) action of the light-refrigeration combination accounts for the greater reduction in gloss. In a cycle containing longer exposure periods, the increased cracking is induced by the greater amount of film deadening which takes place between temperature changes. Compare cycles 10 and 12, Fig. 5.

TABLE VII.—SUMMARY OF OBSERVATIONS ON VARNISH NO. 5.

Gum: Ester and Congo. Oil: 14 gal. Tung and 35 gal. Linseed per 100 lb. of gum. (See Table I.)

Cycle No.	Weathering Agents[1]	Exposure Period	Development of Deterioration	Final Condition after 35 Days' Exposure	Decrease in "Glarimeter" Reading
1	L	Continuous	Dulled 144 hr.	No definite cracking; some slight pitting, and considerable dulling	4.0
2	W	Continuous	Blue cast 54 "	Considerable dulling; no cracking; slight bloom	2.0
3	R	Continuous		Good condition	0.0
4	W-L	3 hr.	Blue cast 15 "	Only slightly pitted; no definite cracking	1.0
5	L-R	3 "	Minute cracking and pitting 102 "	Minute hair-line cracking and pitting	1.0
6	W-R	3 "	Blue cast 81 "	Good condition	0.0
7	W-L	18 "	Fine cracking 90 " Slight blue cast 108 "	Considerable 120 deg. angular cracking	2.0
8	L-R	18 "	Minute cracking 72 " 522 "	Fine angular cracking	2.0
9	W-R	18 "	Slight blue cast 72 "	Good condition	0.0
10	L-W-R	3 "	Slight blue cast 54 " Minute cracking 135 "	No marked cracking; only crack centers and pits	1.0
11	L-W-R	9 "	Slight blue cast 63 " Fine cracking 81 "	Considerable 120 deg. angular cracking	1.5
12	L-W-R	18 "	Slight blue cast 72 " Fine cracking 90 "	Considerable 120 deg. angular cracking	2.0

[1] L = Light; W = Water; R = Refrigeration.

Conclusions for Varnish No. 4.—Apparently, a severe deteriorating effect on this type of varnish is the deadening of the film by the light. Subsequent temperature changes induce the stress-strain cracking. Wetting results in considerable absorption of moisture with softening of the film and an intensified deadening activity of light.

Accelerated Tests of Varnish No. 5

The progress of the deterioration and the final results have been summarized in Table VII and Fig. 7.

Discussion.—Although this varnish shows a slight blue cast when wet, the introduction of the tung oil considerably increases its water resistance as compared with that of varnish No. 4. Due to this increased resistance, the intensified light effect in the water-light change is very much reduced, while the deadening effect of the long light exposures becomes the major deteriorating agent. The subsequent temperature changes induce the stress-strain cracking, Fig. 7. The temperature effect in a light-refrigeration change is very much greater than in a water-light change, which accounts for an earlier, but very minute, cracking after a long light exposure under the light-refrigeration cycle. In the light-refrigeration cycle with short exposures, only the chipping action was noted, as on varnish No. 4. See photomicrographs, Fig. 6.

7. L-W 18 hr. 10. L-W-R 3 hr. 12. L-W-R 18 hr.

Final Condition.

Fig. 7.—Typical Deteriorations of Varnish No. 5 in Accelerated Weathering (Actual Size).

Accelerated Tests of Varnish No. 6

The progress of the deterioration and the final results have been summarized in Table VIII.

Discussion.—This varnish was the most water resistant of any of the varnishes so far considered. Only in the continuous-water cycle was there any indication of permanent discoloration, which was a slight bloom and not a whitening effect. A trace of the mushy condition usually produced by water on the linseed oil films developed in the continuous-water exposure and the water-light cycle with long exposures. This was evidenced by a slight pitting.

The loss in distensibility due to the light exposure progressed only far enough to produce a noticeable deterioration in the light-refrigeration cycles. See Table VIII. Since the moisture content of the film is low, and the temperature variations are great, any loss in distensibility of the film would reveal itself under this cycle. Microscopic examination showed that this deterioration was the same surface chipping as previously discussed under varnishes Nos. 4 and 5.

Because of greater amounts of tung oil, the effect of water on the linseed oil and rosin previously observed in varnish No. 1 was almost completely overcome, rendering this varnish very water resistant. The brittleness of the gum was overcome by the high total oil content.

ACCELERATED TESTS OF VARNISH NO. 7

The deterioration of this varnish is much similar to the previous one, except that there was no evidence of a softening effect due to water. A slight bloom developed under the continuous water cycle. Also, there was some general deterioration under the light-refrigeration combination, indicating a gradual deadening of the film, but this was not as extensive as with varnish No. 6. Probably because of the presence of a somewhat softer gum, and the complete absence of linseed oil, this film apparently retained its distensibility more tenaciously under the light exposure than varnish No. 6, in spite of its lower total oil content. In all respects, this varnish proved the most enduring of those tested in these experiments.

TABLE VIII.—SUMMARY OF OBSERVATIONS ON VARNISH NO. 6.

Gum: Limed Rosin. Oil: 72 gal. Tung and 28 gal. Linseed per 100 lb. of gum. (See Table I.)

Cycle No.	Weathering Agents[1]	Exposure Period	Final Condition after 35 Days' Exposure	Decrease in "Glarimeter" Reading
1	L	Continuous	Considerable dulling	5.5
2	W	Continuous	Considerable bloom; traces of pitting	3.5
3	R	Continuous	Good condition	0.5
4	W-L	3 hr.	Good condition	0.5
5	L-R	3 "	Badly dulled; considerable general deterioration	2.0
6	W-R	3 "	Good condition	0.5
7	W-L	18 "	Trace of pitting	1.0
8	L-R	18 "	Badly dulled; considerable general deterioration	2.0
9	W-R	18 "	Good condition	1.0
10	L-W-R	3 "	Good condition	1.0
11	L-W-R	9 "	Good condition	1.0
12	L-W-R	18 "	Good condition	1.0

[1] L = Light; W = Water; R = Refrigeration.

In no case was the deterioration in varnishes Nos. 6 and 7 sufficiently characteristic to warrant photographic reproduction.

GENERAL INTERPRETATION OF RESULTS

On the basis of the experimental results, the progress of the disintegration of the varnishes may be broadly divided into two distinct steps, which apparently have a cause and effect relationship to each other.

The first step involves an actual deterioration or deadening (chemical and physical changes within the film structure) due (1) to the action of the light, with its lesser auxiliary heat (at 40° C.), and (2) the action of moisture. Both of these act alone and together toward promoting those changes within the film which finally reduce the distensible properties, and may be called causative factors.

The second step is that of revealing the deterioration induced during the first. Primarily, temperature variations are most effective in revealing these changes by setting up stresses within the film. Essentially this is true of any temperature change above or below freezing. However, when the lower temperatures are reached, a new force enters into play, as has been previously pointed out, namely, the expansion due to a change of state of the liquid phase (as water) within the film.

Varnish No. 1. Varnish No. 2. Varnish No. 3.

Final Condition.

FIG. 8.—Deterioration on Out-door Exposures (Actual Size).

Humidity changes constitute another factor in weathering, but on account of the limitations of the equipment it was eliminated in this investigation by treating it as a constant. Previous investigations[1] on the physical properties of paint and varnish films have shown that the distensible properties of these films are considerably increased by absorbed moisture. Therefore, the revealing forces, such as the stresses set up by temperature changes, will be greater under low humidity conditions, when the liquid phase content of the film is lowered. Also, the increased activity of the light in the presence of excessive moisture has been repeatedly indicated throughout the previous discussion. This is entirely in accord with our knowledge of many such photochemical reactions, and previous observations on paint films.

Heat, *per se*, was eliminated as a variable in these experiments, except in so far as it occurs as a constant auxiliary to the factor with which it is generally associated, namely, light. It is known, of course, that heat promotes the progress of the distensibility-reducing changes within the film; quite markedly at higher temperatures (say 95 to 100° C.) and very much more slowly at lower temperatures.

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[1] H. A. Nelson, "Physical Properties of Varnish Films Indicated by Stress-Strain Measurements," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part I, p. 290 (1923).

The reader is referred back to Fig. 2 for a graphic representation of the probable process of deterioration of a varnish film.

COMPARISON OF RESULTS WITH OUT-DOOR EXPOSURES

An out-door exposure was started with these seven varnishes on February 2, 1924, and has been under exposure for ten weeks so far. During this time, the relative ratio of the out-door weathering factors was 1 hour of water (actual snowing or raining) to 5.4 hours of sunlight and to 10.4 hours of refrigeration (temperatures below 0° C.). A summary of the present condition of these panels is given in Table IX and also in Fig. 8.

As will be noted from the weathering ratios, these out-door panels have been subjected mainly to an excess of refrigeration and temperature changes, with the total of sunlight relatively small. From observations made in the accelerated tests, a predominance of fine angular cracking in the deterioration is to be expected. Upon examination of the progress of the cracking (Fig. 8) of those varnishes which had cracked, this conclusion is verified, especially in varnish No. 3, which had previously been observed as being the most sensitive to temperature changes. The first cracking on the three cracked varnishes, Nos. 1, 2 and 3, occurred at about the same time, the twenty-first day of exposure. In the accelerated system, cycle 12, varnishes Nos. 1, 2 and 3 cracked in 72, 90 and 90 hours, respectively.

TABLE IX.—SUMMARY OF THE PRESENT CONDITION OF THE OUT-DOOR EXPOSURES.

VARNISH No.	CONDITION AFTER 70 DAYS' EXPOSURE	DECREASE IN GLARIMETER READING
1	Finely cracked with considerable whitening	7
2	Finely cracked with no permanent whitening	2
3	Finely cracked with no permanent whitening	1
4	Slight pitting	1
5	Good condition	0
6	Good condition	0
7	Good condition	0

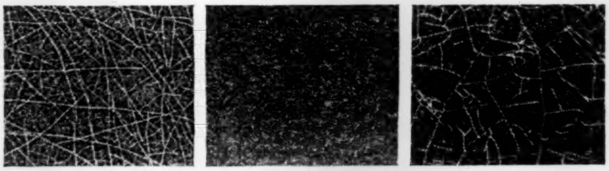
An average of the reduction in gloss under the various accelerated exposures shows that varnish No. 1 has the greatest fall in gloss, varnish No. 2 next, and varnish No. 3 little or none. This same relationship of gloss drop has been duplicated on the out-door exposures, except in that the gloss of varnish No. 3 was affected slightly more than in the accelerated system.

On varnish No. 4 the slight pitting action obtained in the accelerated system, because of the lack of water resistance of the linseed oil film, was again duplicated on the out-door exposures.

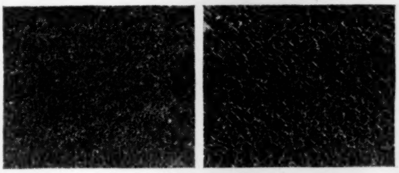
The ratios of the weathering factors of the out-door and the accelerated exposures do not duplicate each other. This undoubtedly accounts for the variations in the two sets of results, but on the whole, they are fairly comparable.

Relationship of Weathering Qualities and Raw Materials Used

Although it is not the stated object of this work to compare relative merits of varnishes or varnish materials, it is interesting to consider briefly the relative qualities of the raw materials as they appeared in the test varnishes during these experiments. For example, in each of those varnishes which had actually cracked, the breaking up of the surface was quite individual and characteristic (see Fig. 9). It might even prove feasible to associate the composition with the type of cracking that occurs.



Varnish No. 1. Varnish No. 2. Varnish No. 3.



Varnish No. 4. Varnish No. 5.

Final Condition.

Fig. 9.—Comparative Deterioration of the Varnishes Under Cycle 12 in Accelerated Weathering (Actual Size).

Gums.—The detrioration due to limed-rosin was quite evident, especially where large amounts of water-resistant oil had not been used and water, due to its emulsifying action, caused considerable permanent whitening. Again, because of the brittleness of this gum considerable oil must be used to overcome the temperature-change effect.

Congo gum, though considerably more water-resistant than the limed-rosin, still seemed to lack somewhat in this property. On the other hand, it was quite soft, thus permitting a rather distensible film in spite of low oil content.

Kauri gum appears quite hard, but especially water-resistant. Thus, it seemed to improve the qualities of the film of a non-water-resistant oil, provided the latter was not present in too great an excess.

Oils.—Tung oil seems to stand out as being especially qualified for improving the water-resisting qualities of the varnish and of increasing its resistance to the deadening action of the light. Linseed oil did not seem to be especially strong in either of these qualities.

FUTURE DEVELOPMENT OF THE WORK

As can readily be realized, because of the extent and importance of this problem, work on the possibilities of accelerated weathering has really only begun. Further investigations are contemplated as follows:

1. Further study of the fundamental weathering factors on other surfaces, mainly paints.
2. Study of other weathering factors that have not been considered.
3. The derivation, from these fundamental data, of a series of standard accelerated cycles, which will approximate the effective ratios of the weathering factors present under various actual service conditions. This would include a calibration of these cycles.

In concluding, the authors wish to acknowledge and express their appreciation for the constructive criticisms and suggestions received from other members of our research organization.

BLOWN OILS

By H. B. Pullar[1]

There has been so much misconception on the part of many engineers and laymen, and so much unwarranted prejudice against asphalt and bituminous compounds made by the treatment of air, and commonly known as "blown oils," that any information tending to clarify this situation at the present time would seem to be of some value. Apparently there has been little written or published on blown asphalts, and many engineers, contractors, chemists, and even experts in bituminous products are apt to consider all blown oil asphalts as short and greasy, having no binding properties, and of no particular value. This misconception seems to be quite universal, notwithstanding that hundreds of thousands of tons of blown asphalts are used every year in the paving and road industry, as well as in the general commercial trade, where they are sold under various trade names and numbers and more commonly referred to as asphalt specialties. Practically every large asphalt or refining company producing bituminous products makes some blown asphalts, but possibly because of the more or less unjust prejudice against these materials they have not been generally marketed as blown products.

For the information of those who are not familiar with how blown asphalts are produced, a short description of the method in general use will be given. A heavy asphalt residuum, more commonly known perhaps as flux, produced in the usual method of refining oil, is heated to a temperature of between 300 and 400° F. When it has reached a proper temperature, depending somewhat upon the source from which the residuum is obtained, the residuum or flux is subjected to a treatment of air. This air is evenly distributed through pipes located in the bottom of or throughout the still, the distribution being made by drilling these pipes with holes varying from $\frac{1}{4}$ to $\frac{1}{2}$ in. in diameter. A large volume of air is forced through the hot residuum, which violently agitates the entire mass. This causes a reaction to take place in the residuum, gradually changing it into hard asphalt, the change depending upon the length of time of treatment and the temperature. The longer the time and the higher the temperature, the greater the change. Just what reaction does take place is problematical. It is generally believed that the reaction is simply an oxidizing one, although there has never been any conclusive evidence submitted that this is true, and a careful perusal of the testimony in the blown-oil patent cases does not reveal any conclusive evidence to this effect. Regardless of whether it is an oxidation or polymerization reaction, or a combination of both, the action of the air does produce certain definite results, and gives a product having inherent properties very different from those of products obtained by direct distillation.

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There are three important essentials to consider in blowing petroleum oils, in order to get the best and quickest results. The oil must be at the proper temperature to carry on the reaction. There must be a proper distribution of the air throughout the mass. And last, but by no means the least important, the fumes generated must quickly and easily pass off as fast as they are produced. It does not seem to make any material difference whether the converters are as small as 500 gallons capacity, or as large as 25,000 gallons; the time of conversion and the characteristics of the finished product are proportional to, and controlled by, the three essentials given above. It is interesting to note that in this conversion from a comparatively liquid flux to a hard asphalt, having as high a melting point as 375° F., the loss due to the conversion is rarely in excess of 5 per cent and may be as low as 3 per cent.

Due principally to the fact that blowing patents were held and controlled in the Middle West, and at that time the only available flux was from the Central or Mid-Continent fields, the early blown asphalts were made principally from the semi-asphaltic oils, and they did have a rather short, greasy appearance. Gilsonite, a solid asphalt product, was used in the higher quality products to overcome this greasy appearance, and to give additional tensile strength and binding properties to the blown oils. Later in the history of blowing, the Texas, California, and Mexican oils were subjected to the same treatment, and while they had many of the characteristics of the Mid-Continent blown products, they did not have the short, greasy appearance.

The results that have been obtained from the use of blown oils in the paving and road industry do not seem to justify the general prejudice against this class of material, and this applies to those roads and pavements made from blown oils from the semi-asphaltic crudes as well as those from the more asphaltic base crudes. Some of the best penetration roads constructed in the country, that have withstood traffic from twelve to fifteen years and are still giving good service, were made from blown asphalts. Many thousands of yards of mixed asphaltic concrete of the Topeka type, and those having a coarser mineral aggregate, such as was used in the Chicago park systems, have given remarkable service, standing up under extremely heavy traffic and in many cases without an adequate foundation. Even large yardages of sheet asphalt pavements have likewise stood up for periods of from ten to fifteen years and are still giving excellent service.

In all of the above-mentioned cases, I refer particularly to those blown asphalts made from the central western crudes, having practically no ductility, which are to-day barred from practically every paving specification. While there have, of course, been some apparent failures from the use of these products, there have likewise been a great many failures of the more highly ductile and straight-refined products. It is generally recognized that lack of attention to the many small but important details of construction of all kinds of bituminous pavements is one of the principal causes of failure, and the failures of the low-ductility asphalts are no more a criterion of the value of blown products for paving in the road industry than is the failure of the more highly ductile products a criterion of the value of those asphalts. It is the successful and the satisfactory results that are of more interest, and if the results are satisfactory in a great many cases, as they have been, there is no justifiable reason for not having a large percentage of the results satisfactory.

The first asphalt fillers for brick pavements were produced from the central western residuums by blowing, and their successful use blazed the trail through opposition and criticism until to-day asphalt fillers are unanimously recognized as the most suitable filler for brick pavements. Yet the irony of fate has decreed that these fillers, which have proved successful through a period of years, are now barred from many of the specifications because of their lower ductility. Even the most enthusiastic adherents of the ductility requirement can hardly justify the necessity of this requirement for a filler.

Blown asphalts made from Texas, California, and Mexican residuums meet with the requirements of practically all the specifications, and thousands of tons are used every year with entirely satisfactory results. Many engineers who approve of their use probably do not know that they are blown products.

The rapidly and constantly changing traffic conditions to which our roads and pavements are being subjected makes the consideration of the use of blown oils particularly important at the present time.

Horse-drawn traffic and narrow-tired vehicles have practically disappeared from our highways, but a new, more dangerous and difficult menace has appeared in the form of heavy trucks, motor buses, and an ever increasing amount of motor traffic. Bituminous pavements are subjected and will continue to be subjected to a more severe rutting and shoving action than ever before. One of the principal ways that this may be overcome is to produce a bituminous binder that will give a harder pavement which will stand up against shoving and resist the impact of the heavy loads. The more general use of blown asphalt cements would appear to be one solution of this trouble. Two of the principal inherent properties of blown oils are high melting point in relation to penetration and a low susceptibility to changes in temperature. Melting point in the past has not been given very serious consideration in specifications for asphalt cement, but under these new conditions of traffic it seems that this characteristic must be given more attention. Shoving and rutting occur in hot weather when the asphalt cement has reached a softening point that will not permit it to withstand the stress and strain to which it is subjected. An increase of 10 to 25° F. in melting point will without question overcome a great deal of shoving and rutting, and particularly when it is accompanied by a lowering of the susceptibility to changes in temperature.

To increase the melting point of a straight-run Mexican asphalt cement 20° F. would mean a reduction in penetration of about 30 to 35 points; whereas an increase of 20° F. in melting point with a blown Mexican asphalt would only mean a reduction in penetration of from 20 to 25. Or to illustrate this more clearly, to change a Mexican asphalt cement having a penetration of 50 to 55 and a melting point of 130° F. to an asphalt cement having a melting point of 150° F., it would be necessary to reduce the penetration to 20 to 25, whereas to change a Mexican asphalt cement of from 50 to 55 penetration and 130° F. melting point by blowing to an asphalt cement having 150° F. melting point, it would only be necessary to reduce the penetration to about 30.

The roofing industry, which uses an enormous tonnage of asphalt —practically equal to all that is being used in the paving industry— has been confronted with somewhat the same problem. It has been found in that industry that if the melting point of a straight-run product was sufficiently high to withstand the heat of the summer sun, the product was so brittle in the winter as to make it very objectionable; while if the product was pliable and satisfactory for use in the spring, fall, and winter months, the melting point was too low to withstand the heat of the summer. Practically all of the large roofers, and a great many of the small ones, have overcome these objectionable features by either blowing, or by blowing and blending, using two or more different grades of residuum to get the desired results.

TABLE I.—PROPERTIES OF BLOWN OILS.

Hours Blown	Asphaltic Oil				75 per cent Asphaltic and 25 per cent Semi-Asphaltic Oil				50 per cent Asphaltic and 50 per cent Semi Asphaltic Oil				25 per cent Asphaltic and 75 per cent Semi-Asphaltic Oil				Semi-Asphaltic Oil			
	Melting Point, deg. Fahr.	Penetration at 77° F.	Penetration at 32° F.	Penetration at 115° F.	Melting Point, deg. Fahr.	Penetration at 77° F.	Penetration at 32° F.	Penetration at 115° F.	Melting Point, deg. Fahr.	Penetration at 77° F.	Penetration at 32° F.	Penetration at 115° F.	Melting Point, deg. Fahr.	Penetration at 77° F.	Penetration at 32° F.	Penetration at 115° F.	Melting Point, deg. Fahr.	Penetration at 77° F.	Penetration at 32° F.	Penetration at 115° F.
1	118	125	TS	TS	TS	TS							TS	TS			TS	TS		
2	124	116	TS	TS	TS	TS			84	TS			80	TS			TS	TS		
3	130	96			94	220			96	190			94	190			TS			
4	140	90			102	190	200	TS	108	135	90	170	116	165			92	260		
5	144	75			108	155			122	95			144	100			123	178		
6	146	66			112	135			145	78	57	122	162	78	68	126	163	109	70	195
7	148	57	22	196	118	115			166	60			174	67			181	72		
8	150	48			126	95	40	230	190	48			188	53			208	57	64	90
9	152	42			136	80			204	37	36	82	204	39	37	75	227	50		
10	154	40			144	70	32	156	216	33			220	33			241	47		
11	157	37			150	60			238	25			232	29			249	43		
12	159	34			158	51			255	19	25	54	240	26	23	50	258	39	25	48
13	163	31			167	46	22	110	268	16			251	25			265	33		
14	168	27	15	60	175	44			281	14			255	23			274	27		
15	178	22			181	36			292	13			267	22			283	22		
16	186	19			188	31	16	65	304	12	18	28	275	19	20	30	294	18		
17	194	17			194	30			316	12			282	17			318	16	18	23
18	202	15	8	38	201	29			330	11			290	16			330	15		
19	210	15			206	28			345	10	12	16	298	15			345	14		
20	218	13			216	25	14	33	350	9			312	14			362	12		
21	232	12			222	23			362	8			321	14	15	20	374	11		
22	240	11			230	21			368	7	7	8	334	12			380	10	12	14
23	251	10	6	19	238	20	12	30	284	7			342	12						
24	264	8			246	18			380	6			350	11						
25	276	6			255	16			384	6			358	11	10	12				
26	284	5			261	15			390	6	7	8	366	10						
27	298	5			270	13							371	9						
28	310	5			278	11	10	18												
29	318	5	4	8	288	10														
30	326	5			292	8														
31	332	5	3	7	305	7	9	14												
32					315	7														

TS—too soft.

It would seem that this process could be advisably considered in the paving industry. As a further illustration of what a blended and blown asphalt cement can give, the former illustration can be further exemplified as follows: To raise the melting point of a blown Mexican asphalt cement, 50 to 55 penetration, from 130 to 150° F., it is necessary to decrease the penetration 20 points. If we were to blend this Mexican oil with a semi-asphaltic or central western residuum, we would first find that a blend having a melting point of 150° F. would have a penetration of between 60 and 65, and to increase this melting point by 20° F. it would only be necessary to reduce the penetration approximately 12 points, or to 50 to 55. In other words, an asphaltic blended cement at 60 penetration would give as hard a pavement as a straight-run Mexican product of 30 penetration. This is not simply a theory. A recent examination showed that sheet asphalt pavements in Michigan and Wisconsin, laid in 1911, in which a blend of a blown refined asphalt with a California flux having a penetration of between 70 and 80 was used, were as hard, even harder, than other pavements in the same town made with other asphalts having a penetration of between 50 and 60.

In order that the results of blending and blowing might be more accurately shown, practical test runs were made with straight and blended fluxes. Table I shows the changes that take place in blowing. The blowing time as shown in the table should not be taken as indicative of the length of time necessary to get the desired results, as these test runs were made in order to get some idea of the gradual changes that take place and no effort was made to finish the materials in the shortest length of time. The same results can be obtained in from one-third to one-half the blowing time.

In conclusion, from over sixteen years' experience with blown asphalts in the paving and general industry field, the author can not help but feel that now is the opportune time for engineers, contractors, chemists, and public officials to give more consideration to the possibilities of blown and blended products for paving and road building, and that some of the difficult problems before us at the present time can be solved by their use. Manufacturers who are producing blown products should come forward with their available data. The author believes that in the not distant future the paving and road industry will follow in the steps of the roofing industry in both blowing and blending of oils, and that this will mark an important milestone in the progress of the petroleum and asphalt industry.

DISCUSSION

MR. M. H. ULMAN.[1]—There are certain data lacking in the table, which are essential for proper interpretation of the results. The penetrations and softening or melting points do not furnish information as to the adhesiveness of the various products and as the ductility test is an indirect measure of this, I should like to have information as to the results obtained in this test. **Mr. Ulman.**

It also would be of value to know the effect on the binding power or adhesiveness of the blown asphalts prepared from straight run or blended crudes correlated with the test data on penetrations and softening points.

MR. H. B. PULLAR.—I can answer that for you to a limited extent now. On blowing a straight Mexican product, the data for which is given in Table I under the heading "Asphaltic Oil," the ductility varies between 75 and 100 cm. until the melting point of approximately 140° F. is reached, after which there is a very appreciable reduction in the ductility. **Mr. Pullar.**

MR. PRÉVOST HUBBARD.[2]—Does that apply to all the blends? **Mr. Hubbard.**

MR. PULLAR.—No, that just applies to the first column in the table, a Mexican flux. On the blended products, even a short blowing very materially reduces the ductility. In the Mexican flux the ductility very sharply drops off at a melting point of 140° F. and when a melting point of 168° F. with a penetration of 25 is reached, the ductility drops down to a ductility of about 5 cm. In connection with the blowing of a Mexican flux, a peculiar characteristic has been found, and that is in blowing this flux to an asphalt cement having a penetration of about 50, there is an appreciable ductility at the lower temperatures. The ductility of this asphalt cement at 77° F. as obtained in three different laboratories was between 90 and 100 cm. At 32° F. this same asphaltic cement showed a ductility of 6.5 cm. in one laboratory, 12 cm. in another, and 11 cm. in the third. In other words, the blowing, to a certain extent, seems to increase the ductility at lower temperatures, and does not seriously interfere with the ductility at the higher temperatures. After a certain period, however, the ductility is rapidly reduced, and this is particularly true with the blended products. In practically all of the blended products after **Mr. Pullar.**

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[1] Assistant Engineer of Materials, Pennsylvania State Highway Department.

[2] Chemical Engineer, The Asphalt Association, New York City.

Mr. Pullar. reaching a penetration of 75 it is very difficult to get a product having a ductility of 10 cm. or more. Most of them drop down to about 4 or 5 cm., and even as low as 2 or 3. In a blend of 75 per cent semi-asphaltic and 25 per cent Mexican oil, the ductility almost disappears after a penetration of 50 is reached.

Some pavements of which I made an inspection were all made from a straight-blown, semi-asphaltic oil, which was fluxed back with an untreated California flux. The ductility on this mixture was about 6 cm. and the penetration at which the pavements were laid varied between 70 and 100, most of them being laid between 80 and 90. These pavements a year ago were in very good condition. The only defects noted were a few cracks which were not objectionable, and which did not show any appreciable wear. The concrete people have very amply demonstrated in a practical way that cracks are not such a serious objection to a pavement, and that they can be more easily and economically repaired than either ruts or shoving.

Mr. Skidmore. MR. HUGH W. SKIDMORE[1] (*by letter*).—Mr. Pullar offers a very interesting account of the history of blown oils and bitumens. He makes a strong plea for the use of such materials in the paving industry, displacing partially or entirely the present tendency that he says exists for straight-run Mexican materials.

He discusses the change in character and speed of traffic and goes on to say that with the present asphaltic material in hot-mix pavements, more and more shoving and rutting may be expected and as a cure for this condition, he suggests the use of blown materials. He goes on to state that not only might blown Mexican asphalts be used but that a better arrangement would be the combining of blown Mexican with blown Mid-Continent oils. The theory, which he seems to be proceeding on, starts from the premise that the asphaltic binder is the primary desideratum so far as the structural stability of the paving mixture is concerned. Such a conception is not the correct one and will only lead to trouble with the mixtures. For many years such a theory regarding asphaltic pavements has existed in the minds of a great many engineers and paving experts but actual results under modern traffic conditions, together with extensive research of mixtures during the past few years, have demonstrated beyond a single doubt that this theory is erroneous. The character of the bitumen used as a binding medium has, of course, some effect upon the serviceability of the mixture. However, according to the fundamentals of mixture designing, we are building structures composed of mineral aggregates in a mass, cemented together by means of a "glue" which, in the case

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[1] Consulting Engineer, Chicago Paving Laboratory, Inc.

Mr. Skidmore.

of asphalt mixtures, is asphaltic cement. By a proper selection of aggregate materials, the voidage may be reduced to an absolute minimum, requiring in consequence the minimum of binder, which means that the thickness of the film of binder surrounding the particles is very much reduced from that which obtained in paving mixtures laid under the practice as it existed until recently.

By such proper attention to aggregate grading, modern mixtures are developed which produce surprising strength and stability almost regardless of the exact nature of the binder, again demonstrating that the problem of stable mixture design, to produce pavements able to withstand the displacing effect of heavy traffic, resolves itself into that of the proper selection of aggregates to produce maximum density or low voidage and, after reaching this condition, using just enough bitumen to bind the particles together, that is, approximately that required to fill the voids. This conception of mixture designing reduces to rather a secondary position the asphaltic material itself. In fact, it can be shown by actual laboratory results that pavements of vastly superior structural strength can be produced by this conception of design, using asphalts of so much greater softness than is now common practice, as to be almost startling. For example, it can be shown that the use of asphalts of 100 or more penetration at 77° F. will produce mixtures of several times the tensile strength of normal mixtures according to the old theory in which comparatively hard asphalts of, say, 40 penetration were used.

Mr. Pullar proceeds to point out the general use of blown materials in the roofing industry and attempts to draw a corollary between this and the paving industry, stating that inasmuch as the roofing industry has used blown materials to great advantage, there would seem to be no reason why the same condition would not exist in the paving industry. The mere statement of this comparison between the two industries certainly offers no proof whatsoever of the desirability of using blown asphalts in paving work, as the two industries present entirely different aspects so far as service conditions are concerned.

As will be seen from a consideration of placing the mineral component of the structure first in order of importance, the asphalt must then be selected mainly because of its adhesive ability; in other words, other things being equal, the more adhesive the binding material, the better it will serve its purpose as a "glue" to hold the particles in place. Furthermore, the greater the internal stability of the composition, because of the low total voidage together with the minute size of the voids, the less important becomes the matter of

Mr. Skidmore. binder, although, of course, it will always be desirable to secure a material of high adhesive ability. Therefore, from the well-known fact concerning asphalts, it would appear that, all other things being equal, the softer bitumens would be desirable because they are always more adhesive than the same material of a harder consistency. During the past few years, engineers have generally come to the use of harder asphalts for paving work in an effort to overcome structural shortcomings of the mixture. If it can be shown that structural stability is more properly controlled by means of aggregate than asphalt, then there no longer exists a very strong argument for the use of exceedingly low penetration asphalts, although it will still be proper to select penetrations upon the basis of traffic requirements. For very dense, heavy traffic, naturally somewhat harder bitumens will be required than for extremely light traffic conditions. However, the entire scale or range of penetrations could consistently be moved upward rather than downward as has been the tendency during the past few years.

In the last few paragraphs, Mr. Pullar attempts to point out what can be accomplished by blending Mid-Continent with Mexican asphalts, one or both of which have been blown to a certain extent, stressing particularly the increased melting point available with a lesser reduction in penetration than would exist in case straight-run Mexican was reduced an equal amount in penetration without blowing. This, of course, is an old and well-known fact regarding the blending of asphalts, but in itself would be no particular argument for the use of blown asphalts in paving work regardless of whether or not such blowing would be desirable. So far as ductility is concerned, we agree with him that somewhat lower ductilities might be of no particular disadvantage and of possible advantage up to a certain point. In other words, the ductility of asphalt at 77° F. in excess of, say, 75 to 100 cm. may represent no practical merit so far as serviceability of the material is concerned in the pavement. Furthermore, with reference to ductility, Mr. Pullar must be familiar with the fact that practically all standard specifications to-day permit the use of materials with as low as 30 cm. ductility at 77° F. He points out that the susceptibility of the material to temperature changes can be materially reduced by blowing. This fact undoubtedly has some very meritorious arguments on its side but in lowering the ductility by any means whatsoever, it must always be remembered that ductility of an asphalt has primarily one value so far as indicating its suitability for paving is concerned, namely, its ability to indicate the adhesiveness of the asphalt. As is well known, straight Mid-Conti-

Mr. Skidmore.

nent blown asphalts of paving consistency have relatively low ductility. They also have low adhesiveness and not because of their ductility but because of this low adhesiveness, they have been largely ruled out of consideration for paving purposes. Not necessarily so the blended asphalts in which a certain proportion of Mid-Continent is used. The suitability of such blended material would, naturally, in a large measure depend upon the amount of the low adhesive material added. Just how far the use of Mid-Continent blown materials could safely be used, is still somewhat a matter of opinion in which a number of paving experts honestly disagree; however, present specifications have apparently compromised rather nicely this honest divergence of opinion.

In summing up Mr. Pullar's remarks, it appears to us that regardless of whether or not his arguments favor a move which would be desirable, he has offered very little in the way of actual proof in support of such argument, and, as has here been pointed out, some of his major points would be seriously criticized as proceeding from an erroneous premise.

SLUDGING TESTS FOR TRANSFORMER OILS: A CRITICISM OF VARIOUS TEST METHODS AND A PROPOSED NEW METHOD OF TEST

By E. A. Snyder[1]

Various attempts have been made to explain the possible reactions which occur in a mineral transformer oil when subjected to heat and oxygen either in the presence or absence of a copper catalyst. In some published articles great pains are taken to discuss the origin and chemical composition of these mineral oils and then attempt to explain the behavior of these oils in transformers when subjected to the action of heat, oxygen and copper. Often they deal at great length with the probable manner in which sludge or deposit may be formed and discuss the various reactions which occur or may occur, and from these theoretical considerations deduce that the phenomena of sludging is dependent upon the formation of oxidation, polymerization and condensation products. Usually no experimental scientific data are given to substantiate most of the claims and evidently most of the conclusions reached are dependent on deductions from theoretical premises.

In order to determine whether sludging in transformer oils is due to oxidation, or to other causes, or to oxidation plus other causes, the following tests were made. In the first series, samples of transformer oil of various grades from the poorest to the best were sealed in glass tubes, some including copper and some without copper. They were maintained at a temperature of 250° C. for five months. No sludge was formed during this period. In some of the samples containing copper, a small amount of copper sulfide was deposited during the first 24 hours but did not increase thereafter. In the second series, three samples of the same oil were placed in as many ovens maintained at 150° C. for 48 hours. One sample was kept in an atmosphere of pure carbon dioxide, another in an atmosphere of pure nitrogen and a third in an atmosphere of pure oxygen. The first two samples showed no sign of sludge while the one in oxygen was badly sludged. The first two samples, due to dissolved oxygen in the oil sample, discolored during the first few hours, but the discoloration did not increase after the oxygen was consumed.

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In another series of tests we endeavored to oxidize oil to the point where sludge would no longer be formed. The oil could virtually all be converted to sludge, for so long as heat and oxygen were supplied, sludging continued. At first sludge formed rather rapidly, but as the most easily oxidized components were sludged out, the rate of sludging diminished rapidly, but never entirely ceased.

These tests indicated rather conclusively that:

1. Heat alone will not produce sludging either by polymerization or otherwise.
2. Heat and carbon dioxide or nitrogen will not produce sludging.
3. Heat and oxygen will produce sludging.

It is thus clear that sludging of transformer oil is an oxidation process pure and simple. This is confirmed by actual experience in the operation of transformers from which oxygen and air have been excluded.

After concluding the above experiments we endeavored to develop a test that would tell us which oils would be least rapidly affected by heat in the presence of oxygen. Such a test would indicate which oil would have the longest life in a transformer, that is, function for the longest time before depositing any sludge. It has been definitely proved in our transformer testing department that when an oil *starts* to deposit sludge, there is an immediate increase in core temperatures, probably due to a slight clogging of the oil ducts. This, of course, means that the oil nearest the core surface will become hotter and sludge more rapidly, for the rate of sludging increases with increase of temperature. Hence, the rate of sludge formation becomes progressively more rapid, and consequently a progressive increase of temperature occurs until finally breakdown of the transformer may occur. Hence the reason for developing a test which will show the length of time an oil will last before starting to sludge.

While working on the development of such a test, many types of tests were tried only to be finally discarded, because the results obtained by the test method were not capable of being checked either by different operators or by the same operator, or because the results obtained were not indicative of the value or life of the oil. Much of this work was performed in our laboratory during the past ten or more years and more recently very extensive tests were made in conjunction with other laboratories working under the direction of Committee D-9 on Electrical Insulating Materials of this Society, to determine the advisability of standardizing one of several methods which are in more or less extensive use in this country and abroad. The results of this work were published in detail in the 1923 report of the committee.[1]

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[1] *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part I, pp. 443–455 (1923).

A very complete report of the methods as tried and the results obtained in various laboratories are there given. This committee unanimously decided that none of these methods is satisfactory, chiefly because when working on identical samples and paying very careful attention to all details, different operators and different laboratories could not check their results. To this finding may be added the following objections encountered in studying this problem in our own laboratory.

OBJECTIONS TO MICHIE TEST (BRITISH STANDARD)

1. The Michie test is operated at a temperature (150° C.) as high as or above the flash point of some transformer oils. Many oils may break down at this temperature in a very different manner than they do at lower temperatures more nearly comparable to the operating temperatures of transformers.

2. The Michie test does not measure the ability of an oil to resist oxidation, but the ability of an oil to resist the catalytic effect of copper. Copper, of course, very materially affects the rate of sludging of a transformer oil, but insulating covering commonly applied to windings of transformers and other exposed copper effectively prohibits the catalytic effect of the copper. In practically all transformers manufactured to-day the ratio of exposed copper to volume of oil is very small and very much less than that present and operative in the Michie test. As it is evidently much simpler and less expensive to remove the catalytic effect of the copper by covering the copper than to find an oil having a long life in the presence of copper, it seems to be the obvious thing to do.

Furthermore, the accelerating effect of copper on an oil is selective, for some oils are accelerated by copper and others are not. For example, we obtained on two oils the following results by the Michie Test:

	SLUDGE, PER CENT
Oil C	0.09
Oil D	1.80

With the "life test" to be described later, we obtained the following results:

	WITHOUT COPPER	WITH COPPER (3.75 SQ. IN. EXPOSED AREA)
Oil C	5 days	5 days
Oil D	18 "	Less than 1 day

Obviously if the oils had been selected by the Michie test, oil C would have been decided upon as being by far the better oil to use, but when judged by the life test, oil D is over three times as good if operated in a transformer having little or no copper present.

3. The Michie test does not measure the life or comparative value of different types of oils in the presence of copper. It simply, as before stated, measures the resistance of oils to the catalytic effect of copper under conditions of the Michie test and is not comparable to the performance of the oil in a transformer in the presence of copper. For example, we have tested two oils both of which will pass the British specifications for the Michie sludge test. The Michie values are about 0.08 per cent sludge for oil A and 0.02 per cent sludge for oil B. But when these oils are placed in transformers or tested in our new life test, oil B has a far longer life than oil A.

4. The results obtained in a Michie test are not comparable, that is, an oil showing a sludge value of 0.09 per cent is not twenty times as good as one showing a value of 1.80 per cent. (See data under item 2, above.)

5. The amount of sludge obtained is entirely dependent on the length of time the test is operated. No real reason can be advanced for selecting 70 hours instead of 170 as the length of time to operate the test. If two oils are tested and the results obtained in one set of tests, when operated for 70 hours, compared with results obtained at 170 hours on the same oils, it will be found that the ratio of difference between the two oils does not remain the same. The following test indicates this very clearly:

Three oils were subjected to the Michie test, excepting that the tests were run for periods of one day, two days, three days, etc., up to twelve days. Selecting the values obtained on those tests operated for one day, three days and twelve days, we obtained the following results:

	SLUDGE, PER CENT		
	1 DAY	3 DAYS	12 DAYS
Oil X	0.3	3.0	8.0
Oil Y	1.0	6.0	9.0
Oil Z	0.5	8.0	13.0

Assuming for the moment that the test results are comparable, an analysis shows that in a one-day test oil X is about three times as good as oil Y, but after a three-day test it is only twice as good and after a twelve-day test very little difference is found, although oil X is still slightly better. In the case of oils Y and Z, after one-day test oil Y is twice as bad as oil Z, but after three days oil Z is worse than oil Y and after twelve days oil Y shows very much better than oil Z. Similar discrepancies may be shown by comparing results on oils X and Z. This indicates that the results obtained in a Michie sludge test do not measure the true relative value of the oils.

OBJECTIONS TO THE FORMOLITE TEST

A formolite test was proposed as a test for measuring the comparative sludging properties of oils. The test actually measures the quantity of unsaturated cyclic hydrocarbons present in an oil and presupposes these compounds to be chiefly or entirely responsible for sludging. In view of the fact that we lack evidence that the formolite test is a fair index of the rate at which oils may oxidize or sludge, the test must necessarily be considered in the light of a hypothesis which needs substantiation by considerable test data before it can be seriously considered.

Furthermore, as shown by the work of Sub-Committee IV of Committee D-9 of this Society, different operators in different laboratories when using the same method and identical samples of oil obtained very divergent results.

OBJECTIONS TO THE "GERMAN NINE" TEST

Another test proposed, namely, the so-called "German Nine" test, prescribed by the engineering societies of Germany as a test for measuring the sludging propensities of an oil, measures the tar acids or acid compounds formed when the oil is subjected to heat and oxidation.

1. This test presupposes that oil sludge is acid in character and that therefore the measure of the acids formed is an indication of the ability of an oil to form sludge. We have repeatedly shown by test that the compounds deposited and called sludge are not all acids. Since this test disregards all other compounds formed, it must be rejected at the outset as being no measure of the desired quality.

2. Another objection to the test is the arbitrary selection of 70 hours for the duration of the test. As previously indicated in discussing objections to the Michie test, we are not concerned with how much sludge we can obtain during a certain interval of time, if the ratio of the results obtained during various intervals changes the ratio of the relative value of several oils.

3. Furthermore, the test is one which requires a high degree of technique and for this reason chiefly, it is very hard to obtain check results in the average routine testing laboratory.

OBJECTIONS TO IODINE ADDITION AND SUBSTITUTION METHOD

Another test that was proposed is the iodine addition and substitution test. The chief objections to this test are:

1. That it measures only the unsaturated olefine hydrocarbons and therefore stops short of the whole truth of what we want to know.

2. The test, judging from work performed by Sub-Committee IV of Committee D-9, apparently is as difficult to check as any of the other proposed tests.

3. The test presupposes that the greater the amount of unsaturated olefine hydrocarbons present, the poorer the oil and the more it will sludge. We lack evidence to support such a theory, but have direct evidence that it is not correct for we have tested oils which proved highly satisfactory in a transformer and which had a long life when tested in the "Life Test" but which had a relatively high iodine value, namely, about 14.

OBJECTIONS TO BROWN BOVERI TEST

The Brown Bovari test as outlined in their House Journal of August, 1922, is also objected to because:

1. Like other tests it measures the amount of sludge formed during a certain definite period of heating and, as before argued, we have no reason for assuming that the time of operation is well founded.

2. The A.S.T.M. committee work has pretty definitely shown that methods based on measuring a quantity of sludge formed during a certain interval of time are practically incapable of being checked.

3. The biggest objection is that the test, even more so than the Michie test, is a measure of the ability of an oil to withstand the catalytic effect of copper instead of the measure of how long it will stand up without sludging when under the influence of heat and oxygen. That this is not a measure of what we want to know is shown in the discussion of this point under the Michie test and under the proposed "Life Test," which follows.

DEVELOPMENT OF "LIFE TEST"

After experimentation with all of the above methods, an attempt was made to devise a method that would be free from the above objections. The results of our work have brought forth the method known as the "life test" and described in detail in the report of Committee D-9 for 1923[1] and elaborated in the 1924 report.[2] Briefly described, this method subjects all of the oil samples to the same amount of heat and oxygen and instead of measuring *how much* sludge is formed during a certain interval, the *time required* to produce the first evidence of sludge is noted. This method has so far shown the following advantages:

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[1] *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part I, p. 448 (1923).

[2] *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part I, p. 638 (1924).

1. The oven is designed so that each sample of oil in the run gets exactly the same heat treatment, for all the samples rotate continuously through the same orbit in the closed oven. This eliminates trouble usually experienced in ovens due to localized zones of varying temperature.

2. The heat regulation is sensitive enough so that the fixed recording thermometer will not vary more than ±0.5° C.

3. The oven is constructed so that accurate temperature measurements can be made on any or all samples as often as desired without interfering with the tests, that is, without opening the oven. Furthermore, temperature readings made in a run lasting twenty days have shown that the temperature of all the samples did not vary over 1° C. from the beginning to the end of the run.

4. Samples can be withdrawn at any time without interrupting the test or run.

5. The test is operated without a copper catalyst and therefore is more nearly comparable to conditions experienced in the transformer.

6. Large-size samples are used to minimize the possible slowing up of the sludging of oil due to the removal of samples of partly sludged oil, which themselves act as a catalyst to promote sludging. The large-size sample also reduces the ratio of surface to volume, thus minimizing any possible catalytic effect of the glass of the beakers holding the samples.

7. The test instead of being run at a temperature of 150° C. is operated at 120° C., which is considerably under the flashing temperature of the oil and besides is nearer to the temperature actually encountered in operation of the transformer. It thus eliminates, at least more so than tests run at higher temperatures, the possible formation of compounds which might be formed at high temperatures, but which are not formed at temperatures at which a transformer operates.

8. Test results on the same oil can be checked in various laboratories and by various operators. The same sample was run in two different laboratories, and in one laboratory on two different machines by different operators. The results obtained were:

Laboratory No. 1		18 days	
Laboratory No. 2.	Operator A (Machine No. 1)	18 "	check 18 days
Laboratory No. 2.	Operator B (Machine No. 1)	18 "	" 17 "
Laboratory No. 2.	Operator A (Machine No. 2)	18 "	" 18 "

9. Good and bad oils can be segregated by this test. All types of oil fall, roughly, into four classes: Those sludging in less than five days; those sludging in five to ten days; those sludging in about ten

to twenty days; and those lasting over twenty days. We have tested, in particular, two oils in which oil A gave a Michie test of about 0.08 per cent sludge and the other oil B gave a Michie test of about 0.02 per cent sludge. It is safe to say that if these oils had been tested by several operators using the Michie test, the results would have shown the absolute impossibility of saying which of the oils should be judged the better, for it is the exception to be able to check any closer than these two figures. These same oils, however, when tested in the life test gave the following results:

Oil A	4 days
Oil B	32 "

There was no question here as to how to judge them, and repeated tests always showed the same magnitude of difference. Moreover, in spite of the difficulties of obtaining satisfactory performance tests in transformers, we were able thoroughly to convince ourselves that oil B gave much better service than oil A.

10. By the "Life Test" method it becomes very easy to determine by actual test the catalytic effects of various substances when exposed to the oil, for it is a simple matter to calculate just how much of the material being studied to expose to the oil so as to duplicate in the test the same ratio that is to prevail in the transformer. For example, to study the effect of copper, oils A and B, mentioned above, having a Michie test of about 0.08 and 0.02 per cent of sludge, respectively, were subjected to the life test both without the presence of copper and with the presence of copper, 3.75 sq. in. of copper being exposed to 500 cc. of the oil. The following results were obtained:

	OIL A	OIL B
Without copper	4 days	34 days
With copper (3.75 sq. in. area)	4 "	24 "

It is evident from this test that:

(*a*) Oil B is much better either with or without copper.

(*b*) Oil A is not accelerated by the presence of copper.

(*c*) Oil B in the presence of copper will last approximately five times as long as oil A.

As it is impossible in the Michie test to check any closer than the values of 0.08 and 0.02 per cent sludge for these oils, it is quite impossible to deduce any conclusion other than that oil A is equally as good as oil B. From actual transformer operations we know that the conclusions obtained in the Michie test are false, while those obtained in the life test are correct.

11. By use of the "Life Test," it is possible to tell how much life is still left in an oil after it has been in service in a transformer. We have taken oils which we know to have a "Life Test" of twenty days and run them for ten days in our apparatus. They were then removed and allowed to stand about a week and returned to the apparatus. Invariably they would last about ten days longer before sludge would form. When these same partially oxidized oils in which half the life was destroyed were run in a Michie test, the amount of sludge formed was far more than twice that obtained on the original oils. In other words, the results obtained in a Michie test are not translatable into any figures which give an indication of the length of service to be expected from the oil, while the "Life Test" figures give direct ratios.

This advantage of the "Life Test" is of decided importance in that it makes it possible to test an oil that has been in operation in a transformer for several years or more, and estimate fairly accurately how much longer the oil will last provided operating conditions remain constant.

It may be of interest to add that oil A was produced by a refiner to expressly meet the British specifications of lesst han 0.10 per cent sludge by the Michie sludge test. Oil B was produced by another refiner who had in mind primarily the object of producing an oil that would last longer in a transformer than any other oil on the market. It was to be the "super oil" of transformer oils. It will be noticed that he succeeded in producing an oil which met the British test, but by that test it could not be judged any better than oil A. In the "Life Test" and in actual performance, however, a very decided difference is noted.

OBJECTIONS TO THE "LIFE TEST"

1. Certain objections have been raised to the "Life Test" method, chief of which is the time required to make the test. This, of course, cannot be denied to be more or less of a handicap, but in the absence of any short method equally reliable, we feel impelled to adhere to the one that gives results that are comparable and correct rather than adopt a method whose results are misleading. It is, of course, possible that the refiner operating on known oils could raise the temperature of the test 8 or 9° C. and double the rate of obtaining results, and he might even go further and by running with his unknown oil a sample of oil of known life raise the temperature considerably and obtain fair comparisons.

2. Another objection raised is the cost and bulk of the apparatus.

We feel that both of these can be materially reduced and are at present redesigning the apparatus with this end in view.

3. Another objection is the possible dropping of condensed oil drops from the cover into the beakers. If the air input is sufficient we doubt if this trouble would arise, but in the new design we plan to fasten a cone to the inside of the cover so that oil drops will run down and drop off beyond the beakers containing the samples.

4. One objection that might be serious has not yet been fully investigated, namely, the possibility that when a series of oils of different types are tested at the same time, the vapors from some of the samples may seriously affect the others. It is comparatively easy to determine this and a series of tests will soon be run to establish the correctness or falseness of this assumption. All we can say so far is that although we have already made hundreds of tests on various types of oil, there has not yet been any evidence that trouble of this sort might be experienced. Furthermore, because we operate at comparatively low temperatures and maintain a fairly rapid stream of air through the apparatus, we doubt if a test will show any trouble arising from this source.

Acknowledgment.—The author wishes to state that a great deal of the experimental work in developing this life test was performed by Mr. D. C. Cox of our laboratory and that due credit should be given to him for his thorough and painstaking work.

[For a discussion on Oxidation Tests for Oils, see page 973.—ED.]

AN OXIDATION METHOD FOR MEASURING THE STABILITY OF MINERAL OILS[1]

By T. S. Sligh, Jr.[2]

Introduction

Mineral oils have a tendency to combine with oxygen, especially at high temperatures, forming undesirable oxidation products in the oil.

Oxidation is accompanied by a discoloration of the oil and an increase in its viscosity, the development of acidity and finally the formation of precipitates of an asphaltic nature. In the presence of water and sediment, such as abraded metal particles, dust and the like, the oxidation products are usually partially precipitated as sludges.

Most of the methods which have been proposed for obtaining knowledge regarding the susceptibility of oils to oxidation consist essentially in holding the oil at a specified temperature for a definite length of time in contact with air or oxygen, the extent of the resultant oxidation being evaluated in terms of the amount of oxidation product formed in the oil. None of the proposed methods have come into very general use, apparently on account of their lack of suitability for routine work. The Waters' Test[3] for carbonization value and the Michie Sludging Test[4] for transformer oils and various modifications of the latter are, however, in use in several laboratories.

The oxidation method presented in this paper is the result of an extended investigation with the aim of developing a method or a modification of some existing method which would yield consistent and reproducible results and which could be precisely specified in terms of the essential determining factors. The result of this investigation is here presented as a method for measuring the stability of mineral oils in contact with oxygen.

Nature of Oxidation.—Although the exact chemical reactions involved in oxidation have not as yet been completely formulated it is known that the oil combines with oxygen and gives off carbon dioxide and water vapor with the formation of certain oxidation products in the oil. For the purpose of this presentation it will be sufficient to consider the products of three stages of the oxidation process. These are:

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[1] Published by permission of the Director of the Bureau of Standards of the U. S. Department of Commerce.

[2] Physicist, U. S. Bureau of Standards, Washington, D. C.

[3] U. S. Bureau of Standards *Circular No. 99*, 1920.

[4] *Journal*, Inst. Electrical Engrs., Vol. 51, p. 213 (1913).

1. *Asphaltic Resins.*—These resins are present in crude oils and to some extent in finished oils, and are developed by oxidation. Resins are doubtless largely responsible for the discoloration and the increase of viscosity of oxidized oils. They are soluble in oil and in petroleum naphtha solutions, but may be separated by absorption with animal charcoal or fuller's earth from which the resins may be subsequently extracted. The quantitative determination of resin is, however, tedious.

2. *Asphaltene.*—This product is probably formed by the oxidation of resins and may be precipitated by dissolving the oxidized oil in petroleum naphtha. Asphaltenes are soluble in benzol, carbon tetrachloride and many other solvents.

3. "*Varnish.*"—This seems to be the final oxidation product short of actual combustion and is usually formed as a strongly adherent film on the walls of vessels in which oxidation has taken place, especially if the exposure has been severe. This product is also present to some extent in used oils. Varnish is characterized by its resistance to the action of the ordinary solvents. Pyridine, alone, is reported to act as a solvent.

Of these three products, the asphaltene is most easily isolated and evaluated. Probably for this reason the amount of precipitate obtained from a petroleum naphtha solution of the oxidized oil has been generally used as a measure of oxidation.

The petroleum naphtha precipitate is so used in the present method with certain restrictions as to the conditions of oxidation. There seems to be evidence that this product, asphaltene, is responsible, to a large extent, for the impairment of mineral oils in service.

Factors Affecting Oxidation.—The principal factors which determine the degree of oxidation of a sample of oil during test are:

1. The instability of the oil, measured by its tendency to form oxidation products;
2. The presence of catalyzers tending to accelerate oxidation;
3. The severity of exposure of the sample to oxidizing conditions. This exposure is dependent upon the temperature of the oil, the duration of test, and the degree of contact between the oil and oxygen during the test.

The determination of the oxidation number, a measure of the instability of the oil, should consist in subjecting the oil to a definite exposure to oxidizing conditions with an evaluation of the resultant oxidation.

OXIDATION METHOD

Catalyzers.—In this method catalyzers are excluded unless they are present in the oil sample or are developed during test.

Temperature.—It was found that air baths, ovens and hot plates are, in general, not adaptable for the degree of temperature control desirable for this test. A well-stirred oil bath has been found to be adequate.

Oxidation is accelerated as the temperature is increased, but if asphaltene is to be used as a measure of oxidation, conditions should be such that little or no varnish is formed. Varnish formation is apparently due to severe oxidation of a thin film or small particles of oil and this product is rarely formed in a sample of oil until very appreciable quantities of asphaltene have appeared. For this reason 200° C. has been chosen as the temperature of test, since with most oils varnish is formed in only relatively small amounts for exposures of 2½ hours at this temperature.

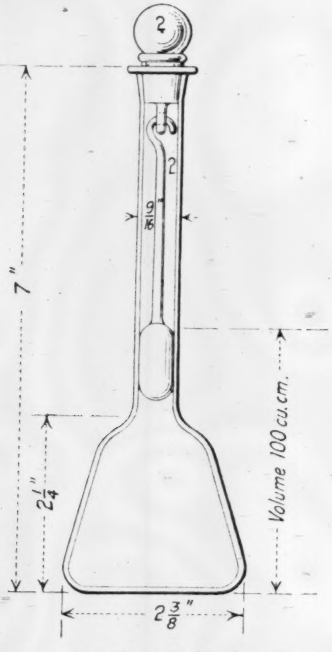

FIG. 1.—Standard Oxidation Flask.
Dimensions are approximate.

Contact of Oil with Oxygen.—Dependence upon convective circulation in open vessels was not found feasible, the use of air in a closed vessel would require a rather large volume to afford sufficient oxygen for the test, and the forced circulation of air or oxygen seemed to introduce undesirable complication of apparatus without promise of definite oil-oxygen contact. For these reasons the use of oxygen in contact with the oil in a closed vessel was adopted.

The degree of contact of oil and oxygen is determined largely by the size of the sample, the size and form of the containing vessel, concentration of oxygen, and some minor factors such as convection in the oil and oil creepage on the sides of the vessel, which factors are, in turn, dependent upon the sample and the oxidation vessel. Agitation of the sample would accelerate the test but would introduce complications in the apparatus and probably uncertainties in the results.

The oxidation vessels are of Pyrex glass,[1] as shown in Fig. 1, having a volume of about 100 cc. and fitted with ground glass stoppers and clamps. The convection plugs which hang from the stoppers serve to suppress gaseous convection which would tend to disturb the temperature equilibrium in the flask and produce results which were dependent in part upon the temperature of the room. These plugs also tend to prevent overheating of the greased seals at the stoppers.

Procedure.—The method of procedure for the test is as follows:

Ten grams ±0.1 g. of oil are weighed into a standard oxidation flask. The air in the flask is displaced with oxygen at approximately 760-mm. mercury pressure and 68° F. and the slightly greased stopper carrying the convection plug is clamped in place. The flask is immersed vertically to a point about 1 in. above the body in a well-stirred oil bath maintained at 200° C. ±1.0° C. and held at this temperature for $2\frac{1}{2}$ hours. The flask is removed and allowed to cool. The oxidized oil is diluted to a total volume of 100 cc. with petroleum naphtha.[2] After 24 hours this solution is filtered and the weight of the precipitate is obtained.

The weight of the precipitate expressed as a percentage of the weight of the original sample of oil and multiplied by 100 is taken as the oxidation number of the oil.

The requirements for duration of test, temperature of test, and form of oxidation flask have been found to be convenient for the general run of oils but no claim is made that they are intrinsically the best. The temperature is near the upper limit for reproducibility of results and the duration of test about the optimum for the average oil with the specified volume of oxygen.

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[1] Flasks are listed as standard oxidation flasks by dealers in chemical glassware.

[2] Naphtha which is free from cyclic and unsaturated compounds and which conforms to the requirements for diluent of the Society's Tentative Method of Test for Precipitation Number of Lubricating Oils (D 91 - 21 T), *Proceedings*, Am. Soc. Testing Mats., Vol. 21, p. 648 (1921).

Oxidation Bath.—The bath is not and need not be closely specified. The essential features are that the temperature distribution shall be good and that the temperature shall be maintained within the specified limits. A change of temperature from 199 to 201° C. increases the amount of precipitate by about 3 per cent. This corresponds to an increase in the precipitation number of an average oil from about 32.0 to 33.0.

Clamps for holding the oxidation flasks in the proper positions should be provided.

A bath of about 3-gal. capacity, 10 to 12 in. in diameter and 8 in. in depth, insulated with the equivalent of 1 to $1\frac{1}{2}$ in. of asbestos magnesia insulation, is suggested. Adequate stirring may be secured by a $2\frac{3}{4}$-in. propeller mounted vertically in a 3-in. tube and driven at about 600 r.p.m.

Such a bath filled with cylinder stock, or some other suitable oil, will heat up to 200° C. at an average rate of about 4° C. per minute with an input of about 2 kw. An input of about 350 watts will be required to maintain this temperature. If automatic temperature control is desired, the regulator may be caused to change the input by about 75 to 100 watts.

The filters may be 25-cc. (No. 3) Gooch crucibles prepared with a filtration pad of finely divided asbestos fiber. About 20 cc. of a suspension of 5 g. of asbestos fiber in one liter of distilled water should provide an adequate filter. The most important point in the preparation of the filters is that of complete disintegration of the bundles of asbestos fiber by shaking.

In filtering, the pressure drop through the filter should be limited to such a value (5 to 10 cm. mercury) as will permit no appreciable loss of precipitate.

Oxygen.—Oxygen such as is commercially available in 100-cu-ft. cylinders is blown into the flasks at atmospheric pressure and temperature to displace the air. The method of filling consists in adjusting the flow of oxygen from the tank to some convenient rate, for example, 2 liters per minute, and passing this stream into the flask for such a time as is necessary to wash about 1 liter of oxygen through the flask. The stopper carrying the convection plug is then quickly seated and clamped.

The oxidation flasks do not acquire the heavy varnish desposit formed by oxidation at 250° C., but usually show a very slight stain on the surface covered by the oil. It is important that the flasks be thoroughly cleaned as any oxidation product remaining will tend to accelerate the oxidation in the subsequent test.

Cleaning the Flasks.—The flasks are cleaned by soaking in alcoholic caustic soda solution, which loosens but does not dissolve the stain, shaking out with clean washing sand, rinsing with strong sulfuric acid to neutralize any traces of soda, rinsing several times with tap water and finally with distilled water. They are then set slantwise in a rack to drain and dry. Care should be taken that the flasks are clean, as any dirt or impurity would probably falsify the test.

EXPERIMENTAL RESULTS

Reproducibility.—A series of tests was run on the "light," "medium," and "heavy" grades of thirty brands of motor lubricants. The tests were run on each sample in duplicate.

The agreement is as follows:

50 per cent better than 0.005 per cent of the sample or 0.5 in oxidation number;
75 " " " " 0.01 " " " " " " 1.0 " " "
90 " " " " 0.015 " " " " " " 1.5 " " "
98 " " " " 0.020 " " " " " " 2.0 " " ".

The poor reproducibility on a few oils was probably due to the fact that the oils contained traces of suspended matter. Repeat determinations on these oils showed about the same results as the first within the limit of reproducibility.

It was noted that, in general, oils having a large oxidation number (70) did not behave so consistently as those having lower numbers. With these unstable oils check results to within 3 per cent of the amount of precipitate could be obtained. The oxidation numbers of these oils ranged from 20 to 75 and there was no apparent relation between oxidation number and either viscosity or flash point.

Turbine oils have been found to range from about 15 to 40 in oxidation number, while transformer oils show values ranging from about 5 to 20.

Effect of Oxygen Pressure.—Tests in which the amount of oxygen in the flask was reduced by a reduction of its pressure showed that the amount of oxidation was directly proportional to the mass of oxygen present in the flask for amounts ranging from 60 to 100 per cent of the content of the flask at atmospheric pressure.

This indicates that it would require a variation of about 2.5 cm. (1 in.) in barometric pressure or a variation of about 10° C. (18° F.) in the temperature at which the flask was filled with oxygen to produce a change of 3.3 per cent in the amount of oxidation product. This corresponds to a change of 1.0 per cent of an oxidation number of 30. It is seen that ordinary variations in temperature and pressure in the laboratory would have small effects on the results. Only under abnormal conditions would a correction be required.

Oxidation in an atmosphere of air yields only about 3 per cent of the amount of precipitate resulting from the corresponding exposure in oxygen. When an atmosphere of carbon dioxide is used, the oil apparently is not affected by heating for 2½ hours at 200° C. No discoloration has been noted and of course no precipitate is formed.

Duration of Test.—Fig. 2 shows the variation of amount of oxidation product with duration of test. It will be noted that the curves are at first concave upwards, that is, the rate of oxidation is accelerated. This has been noted by other observers and is attributed to the effect of the oxidation product already formed upon the rate of oxidation. The reverse curvature for the longer exposures is attributed to the depletion of the oxygen supply. The upper dotted lines joining the curves at 2½ hours are obtained on flasks which are refilled with oxygen at the end of 2½ hours.

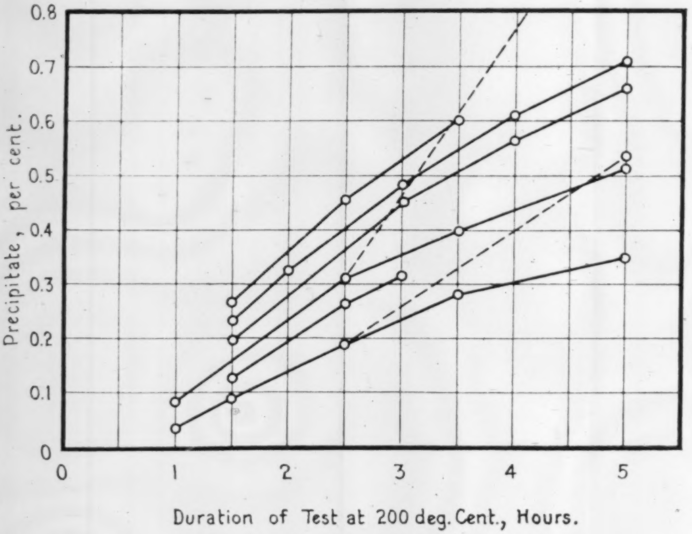

FIG. 2.—Variation of Percentage of Precipitate (10-g. Sample) with Duration of Test.

Dotted lines joining curves at 2½ hours indicate the effect of replenishing the supply of oxygen at that time.

The oxygen supply in the 100-cc. flasks was found to be sufficient to produce at least 0.2 g. of oxidation product. This corresponds to an oxidation number of 200, a value which is far greater than any found for finished lubricating oils.

Effect of Temperature.—Fig. 3 shows the variation of amount of oxidation product with temperature of test, duration 2½ hours. It will be noted that the curves for the various oils show the same general trend. The flattening of the curve toward the higher temperatures is attributed to the conversion of the asphaltene into varnish which adheres to the flask wall and is not evaluated.

Further, this formation of varnish rapidly depletes the supply of oxygen with a resultant decrease in the rate of oxidation. This effect is real and has been noted many times both at from 215 to 225° C. and at 250° C. where the formation of varnish is very much accelerated. Oxidation for thirty minutes at 250° C. yields about equal quantities of asphaltene and "varnish" and the reproducibility of results is very poor.

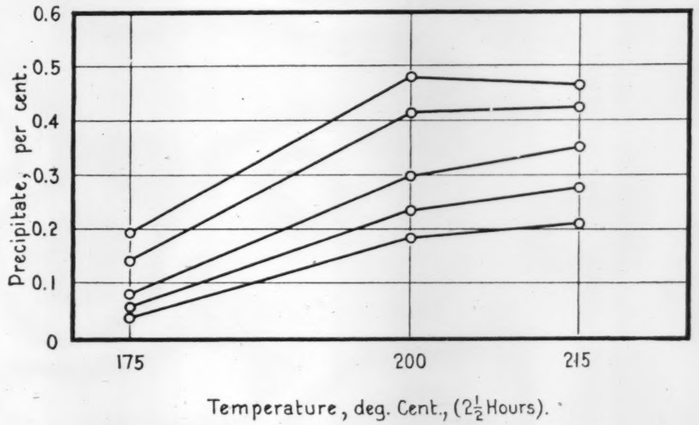

FIG. 3.—Variation of Percentage of Precipitate (10-g. Sample) with Variation of Temperature of Test.

Duration of all tests 2½ hours.

As has been previously mentioned, varnish is the result of severe oxidation of oil. In the body of the sample, this product forms only slowly until after there has been a considerable formation of asphaltene. However, if oxidation conditions are severe, the thin film of oil which creeps up the sides of the flask will be oxidized to varnish and will adhere to the flask wall. It also seems that the oil vapor is severely oxidized as evidenced by the film of varnish which covers the inside of the flask above the oil creepage line when oxidation is carried on at temperatures above 225° C.

Only faint traces of varnish are found after oxidation at 200° C., and this only in the case of oils of high oxidation number (70) or very low flash point (163° C., 325° F.). Somewhat greater precision could probably be obtained with this class of oils by testing at a lower temperature, say 175° C. However, the amount of oxidation product would be reduced to about one-third of the amount produced at 200° C. and the loss in precision in weighing might counteract the gain from reduction of varnish formation.

Variety of Oils Tested.—Positive and reproducible results have been obtained on a wide range of oils such as non-viscous and transformer oils, turbine oils, motor oils and heavy gas engine and tractor oils.

Well-filtered paraffin cylinder stocks, however, do not in general yield weighable amounts of asphaltene even for 8-hour exposures at 200° C. Even at 250° C., although some varnish is formed, the amount of asphaltene is in general too small for accurate evaluation. However, oils of this class are usually rated on precipitation number. When blended with as much as 25 per cent of lighter stock, the blend shows appreciable oxidation.

CONCLUSIONS

The author realizes that only a few of the salient points regarding this method have been investigated in detail, but an attempt has been made to cover the field of variations in factors affecting the test as broadly as possible in the time available. Practically all of this time has been devoted to the question of the conditions for reproducibility of results, and the examination of the effects of variation in test conditions have been for the most part limited to such variations as might affect this reproducibility. The question of applicability to a wide variety of oils has also been investigated.

No attempt has as yet been made to link up oxidation number with service performance of lubricants. This correlation must be worked out for each particular class of service.

The study of the broad question of the factors and treatments which affect the stability of lubricants is still in the future and it is hoped that the oxidation method will facilitate that study.

At the present time a cooperative program is in progress whereby this method will be tried out in a number of oil laboratories on a series of identical samples of oil. The results of this program will indicate the agreement which may be expected between results obtained under average working conditions.

The method seems to possess desirable characteristics which make it suitable for the laboratory examinations of oils. The results of the test are definite, precise and quantitative. Oxidation numbers may be accurately expressed to two significant figures, thus, 34.

DISCUSSION ON OXIDATION TESTS FOR OILS

Mr. Herschel.

MR. W. H. HERSCHEL.[1]—It seems to me that there is an interesting comparison here between Mr. Sligh's test and Mr. Snyder's test in regard to the assumption of the relative effect of high and low temperatures. Mr. Snyder, speaking of the Michie test at 150° C., states that many oils may break down at this temperature in a very different manner than they do at lower temperatures more nearly comparable to the operating temperatures of transformers. Now it isn't quite clear whether that is a hypothesis or whether that is something that has really been confirmed. That is a very important matter because the possibility of reducing the time of test depends entirely on whether you get different compounds at different temperatures or whether you do not. Mr. Sligh's diagrams show no crossing of the lines. If you take different oils and vary the temperature you get the same relative order of resistance to oxidation for the different oils, no matter at which temperature they are tested, and if that is the case, then there is a possibility of saving time in almost any kind of an oxidation test by increasing the temperature. Yet Mr. Snyder apparently hesitates very much to increase the temperature, although he admits that it is possible that it might be done.

Mr. Snyder.

MR. E. A. SNYDER.—The point as to whether oils break up in a different manner at higher temperatures has been brought to the attention of refiners time and time again, and I might say that they are about equally divided in their opinion on this subject. There are quite a number of refiners who have seriously objected to running a sludge test at the high temperature such as used in the Michie test. They claim that the oils will break down and show products which we do not get at the lower temperatures, and they quite logically put the question, "If your transformers will not operate above a certain temperature why ask us to make oil that will stand a temperature much higher than that?" In view of the fact that there is quite a lot of discrepancy in the ideas of the refiners, I would rather have the refiners speak on this point.

Mr. Herschel.

MR. HERSCHEL.—I did not have transformer oils solely in mind. It is a general question and applies to the oxidation of all petroleum products. If it is true that you get different products at one temperature than you do at another, then the question would be whether at the high temperature used by Mr. Sligh you get a fair indi-

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[1] Associate Physicist, U. S. Bureau of Standards.

Mr. Herschel. cation of the relative excellence of oils which are in practice used at a much lower temperature.

Mr. Sligh. MR. T. H. SLIGH, JR.—It seems from all I have been able to gather that most people have a hesitancy about testing the oils at the higher temperatures. I think that our work shows quite definitely that if you go much above 200° C. you get the conversion from asphaltene into varnish, which you do not evaluate and you begin to get discordance in your results and you cannot check yourself, but I have not found any evidence nor has any evidence been presented that indicates that oxidation at 120 or 150° C. is essentially a different process from oxidation of 200° C. and I want to say that if there is any such evidence I should certainly be very glad to hear of it. This work of ours, of course, started in connection with lubricants for internal combustion engines, and there we do have temperatures up to 200° C.

Mr. MacPherran. MR. R. S. MACPHERRAN.[1]—I might say that we run our transformer oils along similar lines to the methods suggested by Mr. Snyder, except that we hold ours for six weeks at a temperature between 160 and 190° F. It seems to give a very good indication of the quality of the oils, but the test is altogether too long. It indicates how it will work out but it makes you wait six weeks for the answer.

Mr. Snyder. MR. SNYDER.—There is one small point I want to bring up. I sent Mr. Sligh some samples of transformer oils marked 1, 2 and 3. No. 1 was the regular grade of transformer oil which is used to a great extent by a number of companies. It had a "Life" test of 17 to 18 days. No. 2 had a "Life" test of 7 days, and No. 3 had a "Life" test of about 90 days. No. 3 was a very, very good oil, there is no question about it. From an operating standpoint it is possibly ten or twelve times as good and has ten to twelve times the life of a regular oil. I sent those to Mr. Sligh and I should like to have his figures on "oxidation value" on those three samples for comparison with "Life test" figures to see whether they line up in the same order.

Mr. Sligh. MR. SLIGH.—For No. 1, I get 11.7 oxidation value; for No. 2, I get 1.4 oxidation value; and for No. 3, I get a trace of precipitate, you would probably call it one-tenth in oxidation value; that is for a 2½-hour exposure. Now it is quite evident that one oil that is twice as good as another may not give twice the precipitate or may give more than twice. However, I might point out, to save myself, that out of three chances, I am right twice.

Mr. Snyder. MR. SNYDER.—Those were three straight oils. I will make arrangements to give Mr. Sligh some oils that got us into trouble and we will see how further tests compare.

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[1] Chief Chemist, Allis-Chalmers Manufacturing Co.

STRUCTURAL TIMBERS: DEFECTS AND THEIR INFLUENCE ON STRENGTH

By J. A. Newlin[1] and R. P. A. Johnson[2]

The non-homogeneous character of wood and the many factors which affect its strength have long caused it to be regarded as an erratic structural material of indefinite strength. On the other hand, its low cost compared with other structural materials, its availability, its exceptionally high strength for weight, and its ease of working, at the mill and in construction, have maintained it in the structural field and will continue to do so. In the past, the characteristic variations of wood were not so important as at present, since timbers were cheap and easily obtained in large sizes and almost clear grades. The clear grades, by practically eliminating defects, removed one of the greatest sources of variability, and the large timbers available permitted the use of high factors of safety.

But conditions have changed rapidly in the past twenty years. There is now a scarcity of large and high-grade timbers, with corresponding great increase in prices, and many species (white pine, black walnut, yellow poplar, beech, and others) have practically disappeared from the structural field. In spite of these facts, modern construction is requiring larger and better material to carry the increased loads of larger structures and heavier equipment. Hence, the old method of specifying clear timber and using a large factor of safety along with questionable basic strength figures can not continue. Definite information as to the strength and variability of timber must be made available for the engineer and architect.

Practically all of the strength tests which supply such information have been made since 1900. The size of test specimens has varied from that of tiny specimens, handled with tweezers, for determining differences in strength between springwood and summerwood to that of large-size bridge stringers[3] and of columns 12 by 12 in. by 24 ft. long. The tests conducted at the U. S. Forest Products Laboratory have been of two main types: namely, (1) Tests of small clear specimens, to afford data for the comparison of the inherent qualities of the species[4] and to determine strength-moisture relations and the effect of duration of stress, and (2) tests of small and large specimens containing defects, to determine the influence of defects on the strength. The resulting data have been made the basis of the Department of Agriculture's grading rules which divide timbers into groups or grades to which minimum strength values can be assigned. The test data also determine the proper factors to be applied to the average strength figures derived from small clear specimens in order to obtain safe working stresses.

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[1] Chief, Section of Timber Mechanics, U. S. Forest Products Laboratory, Madison, Wis.

[2] Engineer in Forest Products, U. S. Forest Products Laboratory, Madison, Wis.

[3] Detailed data for a large portion of tests of structural timbers are given in U. S. Department of Agriculture *Bulletin No. 108*.

[4] "Mechanical Properties of Woods Grown in the United States," Recorded in U. S. Department of Agriculture *Bulletin No. 556*.

It is not the intent of the present paper to take up all classes of timbers and the factors which influence the strength of each. It will be confined rather to a discussion of beams, particularly to the influence of defects on their strength, together with suggestions as to how the desired minimum strength may be insured and as to the ultimate possibility of controlling strength by the limiting of defects.

DEFECTS

A defect in a timber is any irregularity occurring in or on the wood that may lower any of its strength properties. One of the fundamental characteristics of wood is the difference in its strength with and across the grain. Roughly, wood is sixteen times as strong in the direction of the grain as across the grain. It is this difference in the strength with different angles of the grain which accounts for the serious weakening effect of most defects.

Checks and Shakes.—Checks and shakes are local wood failures which occur either in the living tree, or during seasoning. Checks are lengthwise separations along the fibers and across the growth rings and shakes lengthwise separations between the growth rings. Checks are commonly due to seasoning; shakes seldom develop unless they were present to a certain degree in the standing tree.

The checks which develop with seasoning are due largely to the drying of the wood from the outside toward the center. Drying is accompanied by shrinkage. With the exterior drying faster and shrinking more than the interior, progressively increasing stresses are set up which often result in failure. Because of the greater difference between the moisture content of interior and exterior portions of large timbers as compared with dimension stock, the rupture is more severe in the larger sizes.

Cross Breaks and Compression Failures.—Cross breaks are tension failures usually resulting from local abnormal longitudinal shrinkage. Such shrinkage is characteristic of "proud" or "compression" wood, which can usually be detected in fir and pine by the absence of sharp contrast between springwood and summerwood.

Compression failures occur as the result of stresses in the standing trees due to wind, stress developed when the tree falls, and at times may be the result of rough handling of logs or timbers. These defects are limited in extent and occurrence, and while often difficult to detect they may usually be seen in large timbers before they seriously affect the strength, and the material may be avoided. See Fig. 1.

Cross-Grain and Knots.—Cross-grain is the general term used to describe any departure of wood cells or fibers from a direction parallel to the axis of the piece. There are a number of kinds: spiral, diagonal, wavy, dip, and curly and interlocking grain. The defect is best measured in structural timbers by the slopes of checks, which always follow the direction of the grain. Limits on cross-grain in structural timbers are intended to apply only to spiral and diagonal grain;[1] the other forms are usually due to knots, and knot limitations can be depended upon to control them. The damage done by knots is due not to the fact that the material composing them is inherently weaker than normal wood but to the combined operation of several factors, the most important of which are cross-grain and checking.

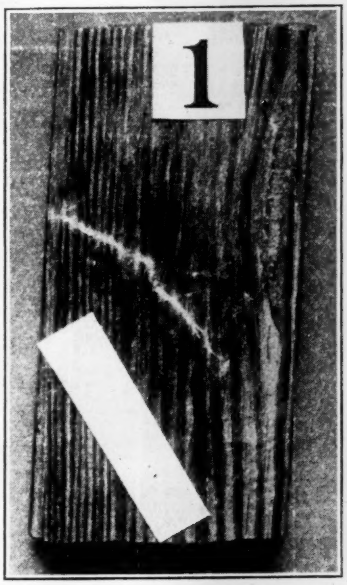

FIG. 1.—"Compression Failures" in Southern Yellow Pine That Occurred in the Living Tree.

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[1] See "The Effect of Spiral Grain on Strength of Wood," by T. R. C. Wilson, ***Journal of Forestry***, Vol. XIX, November, 1921.

In order better to understand the injury we must consider the effect of knots in distorting the grain. Fig. 2 shows how knots are formed by the wood fibers of the main body of the tree running out into the limb and how cross-grain is thus developed. Upon the death of a limb the fibers cease to grow out into it, and the new wood which begins to incase the knot shows a decrease in grain distortion. In Fig. 3 is shown the checking in knots which accompanies drying. It will be noticed that the checks extend entirely across the face of the knot and are very prominent and irregular in direction around it.

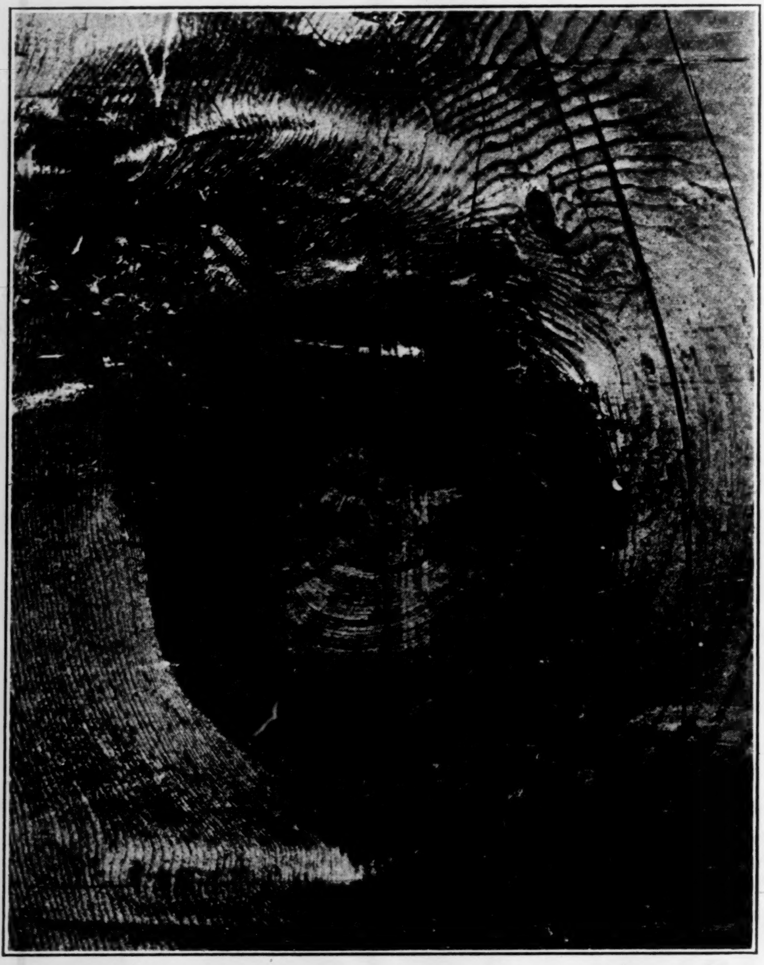

FIG. 2.—Illustration of the Injurious Effect of Checking in and Surrounding Knots.

Decay.—Decay is disintegration of wood substance due to the action of wood-destroying fungi. This action consists in a breaking down of the cell walls which results in a weakening effect even when the presence of the fungus can not be detected visually. Decay is, therefore, an important factor in the strength of a timber, but the determination of its total injurious effect is difficult because the amount of decay visible on the exterior is not a satisfactory indication of the extent to which the strength is affected. Certain types of decay at times continue their destructive action after the timbers have been placed in use. It is therefore necessary to limit decay more rigidly than would seem justified by test.

Other Defects.—The defects above discussed are the ones which it is essential to control in specifications intended to establish definite strength grades. There are others which often give indication of the presence of more injurious defects and as such may be of considerable assistance in grading. Thus, bark pockets and gum spots or streaks are indications of concealed knots; collapse, of severe drying treatments and probable loss of inherent strength; pitch, of shakes and of erratic strength; discoloration and insect holes, of decay attack; and warping, of cross-grain.

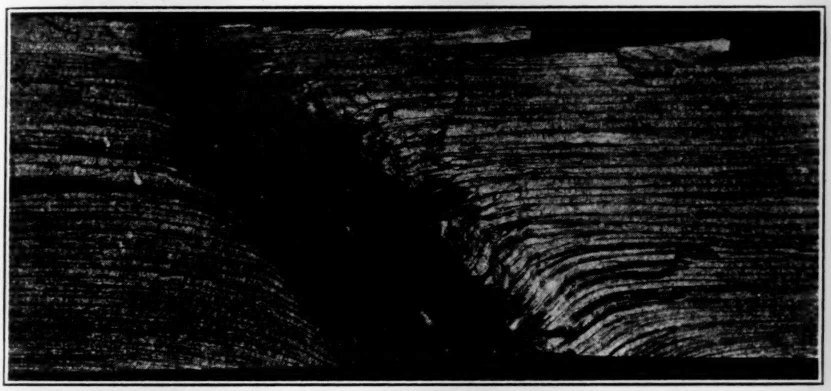

FIG. 3.—Distortions of Grain in and Surroundings Knots.
Note Effect of Checking.

THE EFFECT OF DEFECTS ON STRENGTH

Some defects affect all of the fundamental strength properties, namely, tension, compression, and shear; others affect but one of the properties, while the injury caused by some is due to their combination with still other defects. The manner in which these defects and their combinations affect the strength properties of wood is of fundamental importance in the grading of structural timbers.

Tension.—Tension is affected most seriously by cross-grain, knots, cross breaks, and compression failures.

The ratio of the strength in tension with and across the grain of the wood is larger than for compression and shear, being about 25 to 1 for small clear green specimens and as high as 45 to 1 for air-dry specimens. The amount of injury which will result from cross-grain depends upon the angle the grain makes with the axis of the piece. Even a slight departure from straight grain is a source of weakness, although it does not become very apparent until a slope of 1 in 25 is reached.[1]

The separation of the wood fibers by checks has little, if any, effect upon the strength in tension when the load is applied in line with the fibers. On the other hand, when the load is applied perpendicular to the fibers their separation by checks will cause a direct reduction of the area acting in resistance to tension and, consequently, will reduce the strength. The reduction of tensile strength from checking varies between these two extremes, becoming more and more serious as the angle of grain increases. In small pieces, checking may sometimes reduce to zero the area acting in resistance to tension by actually separating the piece into two parts.

The weakening influence of knots on tensile properties is due almost entirely to cross-grain and the checking introduced. Cross-grain around a knot can be measured on the surface, but that within the knot itself can not be judged in this way. Usually, however, the grain of a knot is at such a wide angle with the axis of the piece that its strength at best can only be considered as the strength of wood perpendicular to grain. Checking, as a rule, will destroy even this, and the effect of the knot proper becomes the same as that resulting from the removal of an equal amount of wood; in addition, the influence of the checking and irregular grain surrounding the knot must be taken into account.

The shape and other characteristics of a sound knot have little influence upon the amount of injury to be expected, since the injury is dependent to a large extent upon the amount of grain distortion. There is very little difference between the reduction of tensile strength caused by knot holes or incased knots and that caused by intergrown knots. The injury from a lack of bond around an incased knot, or the absence of material in a knot hole, is actually less than the injury resulting from the greater distortion of grain around an intergrown knot and from the checking which accompanies it. The amount of grain distortion is dependent upon the diameter of the limb which caused it, but its increase is greater than the corresponding increase in the diameter of limb.

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[1] For a detailed discussion of this subject, see "The Effect of Spiral Grain on Strength of Wood," by T. R. C. Wilson, *Journal of Forestry*, Vol. XIX, November, 1921.

As in the case of checks, shakes have no effect on tensile properties when the load is applied in line with the grain, but any separation of the annual rings would, of course, destroy the tensile strength across the grain. Cross breaks and compression failures, on the other hand, reduce the strength when the load is parallel to the grain.

Compression.—The effect of cross-grain and knots is much less in compression than in tension. The effect of checks and shakes is confined largely to causing an unequal distribution of stresses which results in a reduction of strength through the overstressing of some of the fibers before others.

The compressive strength of wood parallel to the grain is from 6 to 10 times that perpendicular to the grain. This ratio is about the same for both the green and the air-dry material, and is much smaller than the ratio in the case of tension. While the reduction in compressive strength starts with the slightest deviation of the grain, it does not become appreciable until the grain is at a slope of approximately 1 in 10. This difference in the effect of cross-grain accounts primarily for its smaller injury in compression.

Checks in compression parallel to grain tend to close up so that stress is set up over the entire cross-section. The stresses, however, are not of uniform intensity, and failures therefore occur at somewhat lower average loads than if the checks were not present. In fact, checks sometimes do not close until failure has started.

The weakening effect of a knot in compression, as in tension, is due primarily to the cross-grain that accompanies it. However, the weakening effect of cross-grain is considerably less for compression than for tension, and checking in and around the knot is also less injurious. Quite frequently a part or all of the strength across the grain is developed in a knot resisting compression, even when the knot is checked. The net result is a weakening somewhat less than would occur by the removal of the knot proper.

Shear.—Reduction in shearing strength is due almost entirely to the presence of shakes and checks, the presence of knots and cross-grain exerting but little influence. In fact, knots and cross-grain break up the continuity of checks and thus tend to reduce their injurious effects in shear.

Weakening in shear from checks and shakes consists in a direct reduction of the area acting in resistance to shear. Moreover, shakes are usually accompanied by a general weakness in bond between the annual growth rings, which seriously affects the shear strength.

INFLUENCE OF POSITION OF DEFECTS ON STRENGTH

In the past, grading rules have been based upon the size and nature of defects. Their location, which is equally important, has been largely ignored. With uniform or rolling loads the tension and compression stresses in beams decrease from the center of the length of a beam towards the ends and from the narrow faces to center of height. The distribution of stress is the same for both types of loading, although for the same load the stress resulting from the rolling load is twice that of the uniform load. The stresses developed by the third-point method of loading used in testing are constant over the center one-third of the length, and decrease from the center third toward the ends. While this distribution of stresses is different from that under rolling or uniform loading, the presence of uniform stresses in the center third of the length facilitates a study of the influence of defects.

With the same intensity of stress at the center of the length, the uniform, rolling, and third-point loadings will give identical stresses at the quarter points. The maximum difference is at the third points, where the third-point loading gives 11 per cent higher stresses. In the direction of height all types of loading give the same distribution of stresses. The longitudinal distribution of the shear stresses is the same for rolling as for uniform loads, increasing in intensity toward the ends. The vertical distribution is the same for all types of loading and increases in intensity from the edges to the center of height. Checks and shakes along the neutral axis greatly increase the intensity of shear stresses by reducing the area acting in resistance to it.

It is evident from the foregoing considerations that the size of defect allowable is dependent upon the part of the timber in which it is located. The ideal specification would control the location of defects so that a beam containing all of the maximum allowable defects would be equally likely to fail at any of them regardless of their location.

EFFECT OF FACTORS OTHER THAN DEFECTS

In order to fully understand the effects of defects on strength, it is necessary to consider briefly other factors such as density, species, moisture content, form, size or shape, and duration of stress. Taken together, these factors account for all of the chief variations in the strength of wood.

Density.—The specific gravity of the wood substance of all species being practically the same, the density becomes a measure of the amount of wood substance present in a given volume, and hence a measure of the inherent strength of the wood. Dense material of

Douglas fir and southern yellow pine has been defined in detail in specifications of the Society.[1] Applied to these species, the density rules laid down afford a visual method of estimating the quality of inherent strength of timbers.

Although density is the best indication of the strength of clear wood, it can not readily be applied to other species than Douglas fir and southern pine because there is no satisfactory visual method of determining it.

The number of rings per inch as an indication of strength has been much over-rated. It can not be considered as a satisfactory substitute for the density rules previously referred to. However, the maximum and minimum limitation on rings per inch will eliminate the poorest timbers of both Douglas fir and southern yellow pine. Like density, it is inapplicable to other species, especially hardwoods, in which a rapid rate of growth is quite frequently accompanied by strength values better than average.

Species.—The difference in strength due to species has been greatly overstressed in the selection of structural timbers. In any given species it is not uncommon to find some pieces twice as strong as others, although all are sound, clear, and straight-grained. This matter is not as serious as it appears, since the strong pieces are further above the average than the weak ones are below. The difference in the strength of species ordinarily used for structural timbers is less than this variation within a species. Even the average strength of hickory as compared with that of eastern hemlock, when used as a beam or post, is less than 2 to 1.

Moisture Content.—The strength of wood varies with its moisture content.[2] Furthermore, the shrinking and swelling of wood which always accompanies drying and soaking increases the injury resulting from defects, particularly by opening checks along cross-grain and in knots, and by extending shakes.

Size Factor.—Tests have shown that large structural timbers do not show quite the strength that would be expected of them as compared with small clear pieces, even when failure of the large timbers occurs in clear wood.[3] The variation in the strength of beams is a function of their height and this factor has been considered in comparing the strengths of beams of different sizes.

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[1] Tentative Specifications for Structural Douglas Fir (Serial Designation: D 23 – 20 T), *Proceedings*, Am. Soc. Testing Mats., Vol. XX, Part I, p. 704 (1920); Standard Specifications for Yellow-Pine Bridge and Trestle Timbers (Serial Designation: D 10 – 15), 1921 Book of A.S.T.M. Standards.

[2] See "Effect of Moisture Upon the Strength and Stiffness of Wood," by H. D. Tiemann, U. S. Department of Agriculture *Bulletin No. 70.*

[3] See "Influence of the Form of Wooden Beams on Stiffness and Strength—Part II—Form Factors of Beams Subjected to Transverse Loading Only," National Advisory Committee Report No. 181.

GRADING RULES

Selection of timbers exactly in accordance with their strength as indicated by theory and by the results of tests involves too great an amount of work, education and money to be justified at the present time. The present price and limited available supply of lumber, however, do warrant a change from the present very general grading rules to rules which will insure minimum strength values. Grades which, in the opinion of the Society's Committee D-7 on Timber, meet present practical conditions have been formulated. These rules neglect the difference in the intensity of the stresses which occur near the ends as compared with those in the center of the length, the difference in the influence of knots under tension and compression, and the relative distance of shakes and checks from the neutral axis. They do, however, recognize the relation of size of defects to size of timber, and the distance of knots from the neutral axis. They insure minimum strength values and are therefore far in advance of most of the commercial rules in use at the present time.

The correctness of the theory involved and the efficiency of different grading rules were tested by applying them to a number of groups of structural timbers tested, and studying the results. Fig. 4 shows the results of the application of three rules to western yellow pine timbers for the purpose of studying their relative efficiency. This group of tests was chosen for the illustration because complete data on both green and air-dry material were available. As this was the last group of structural timbers tested at the Forest Products Laboratory, portions of the beams including the failures were still available for examination.[1]

The diagram shows the percentage of the clear strength developed by the structural timbers, as given by the ratios of the modulus of rupture of the structural specimens to the modulus of rupture of small clear specimens cut from them. This eliminates largely the factor of density and shows the efficiency of the defect classification.

The structural specimens were divided into four grades, designated as S1, S2, S3, and S4. These grades are based on those given in the U. S. Department of Agriculture *Circular No. 295*,[2] but vary in the degree in which they conform with theory. Figs 4 (*a*) and (*b*) show the application of the principles of the American Society for Testing Materials rule, in that they neglect the difference in stress

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[1] The Forest Products Laboratory has analyzed many other groups of timbers along the same line as the western yellow pine, and this analysis is available to those who wish to examine it at the laboratory. It is not yet determined whether or not this material will be published, and if it is, in what form.

[2] "Basic Grading Rules and Working Stresses for Structural Timbers," U. S. Department of Agriculture *Circular No. 295*, 1923.

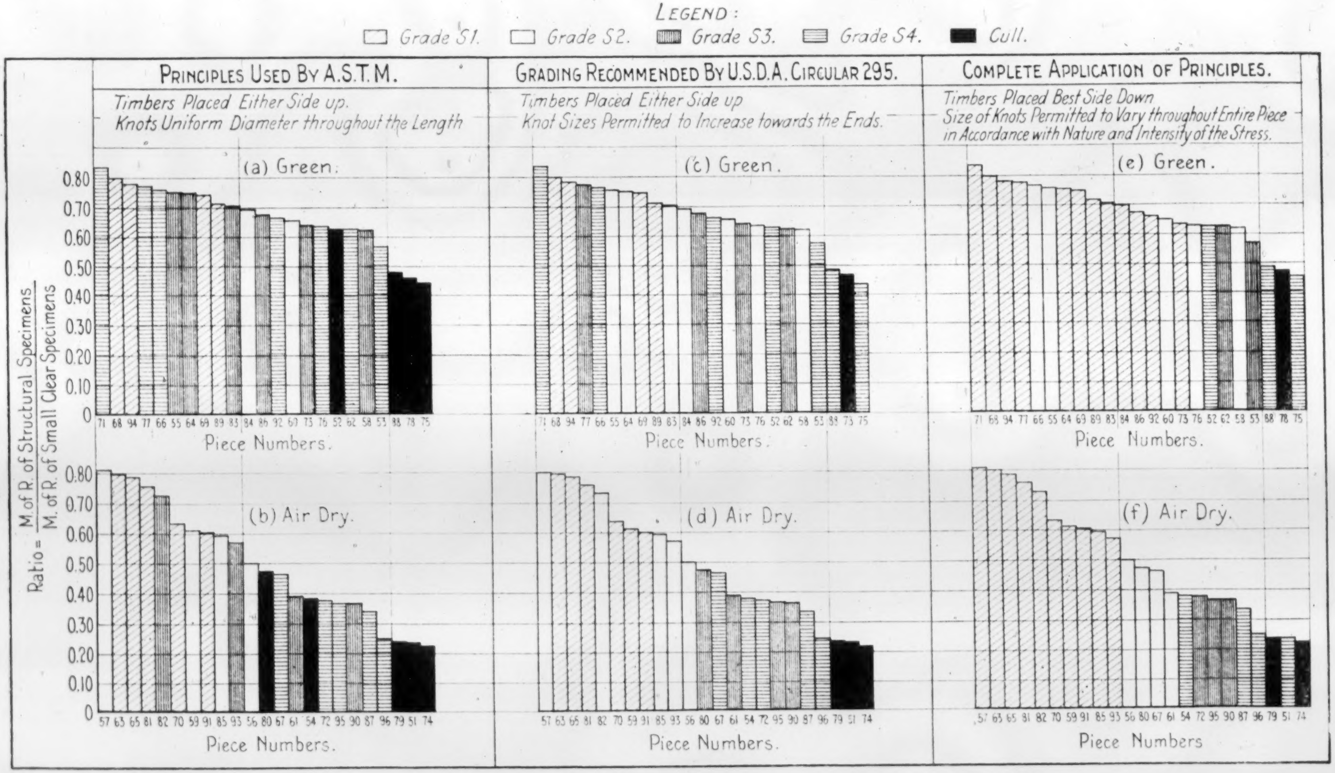

FIG. 4.—Application of Fundamental Principles of Grading to Western Yellow-Pine Structural Timbers.

Efficiency of various degrees of application of theory as shown by ratio of modulus of rupture of structural to small clear specimens.

intensity at the ends and center of the length. Also, this rule does not recognize any difference in the effect resulting from character of stresses in the upper and lower faces of the beams. Figs. 4 (*c*) and (*d*) show the application of the rules given in U. S. Department of Agriculture *Circular No. 295*. These rules allow an increase in size of knots toward the ends of the beam, but not to the extent that theory and analysis indicate is possible. They do not recognize a difference in the effect of knots occurring on the upper and lower faces, nor the position of shakes and checks with reference to the neutral axis.

Figs 4 (*e*) and (*f*) give the efficiency of the rule which takes into consideration not only position in length but the difference in effect of knots on tension and compression faces. This rule represents approximately the ultimate possible limit in grading for strength.

There are excellent reasons for departure from theory in practical rules. The knots, under the Society's rules, are not permitted to increase in size toward the ends because of practical difficulties in grading. The upper and lower faces are graded alike because of the likelihood of a beam being placed wrong side up through carelessness or lack of knowledge on the part of workmen. Control of the position of checks and shakes relative to the neutral axis is not provided for, because of the small difference in intensity of stresses over the center half of height. When these defects occur in the upper or lower quarter of a beam, there is the added danger of their running into the edge, or into the tension and compression failures.

Figs. 4 (*a*) and (*b*) show the grades to be badly mixed. They err, however, on the side of safety. They are intended to insure a certain percentage of the clear strength, and are not expected to prevent overlapping of grades. The overlapping shown is due largely to the defects which determined the grade occurring near the end or top. Thus, a grade made to secure a minimum strength ignores known influences, and therefore includes many timbers of much higher strength than is required for the grade. The poorer classification of the green timbers by all the rules, as is shown in the diagram, is accounted for by the fact that grading rules must consider the strength of timber after it has been in service for a considerable length of time. This consideration requires that in grading green timbers the rules must anticipate injury which has not taken place but which will undoubtedly occur.

Figs. 4 (*c*) and (*d*) show considerable improvement in the classification over Figs. 4 (*a*) and (*b*). The raising of the grade of the timbers with large defects at or near the ends is responsible for the better strength classification shown in Figs. 4 (*c*) and (*d*). It has raised

40 per cent of the timbers the equivalent of one grade which permits a 6.5-per-cent increase in the allowable loads.

The classification shown in Figs. 4 (*e*) and (*f*) is what we can expect to obtain with practically complete application of the foregoing principles, the timbers being placed right side up and the defects controlled in accordance with their position in the length. This refinement appears to be in advance of what is justified under present economic conditions. The application of this rule to the test specimens of western yellow pine raised 75 per cent of the timbers the equivalent of one grade, and the balance of them the equivalent of two grades, above that obtained by applying the principles used by Committee D-7; that is, the allowable loads have been increased 20 per cent.

It is practically impossible to estimate the correctness of fundamental theories back of grading rules when the rules take into consideration only a part of the elements which affect the strength of timber. It is also impossible to check the correctness of the theory and efficiency of grading rules from the results of tests of green material, as previously pointed out, for in interpreting the strength data the ultimate condition of the timber after it has been in service for some time is of great importance. Thus, Figs. 4 (*a*), (*c*) and (*e*) show many low-grade timbers with high strength ratios. This is partially due to the fact that defects did not develop their full weakness and to the fact that the defects in Figs 4 (*a*) and (*c*) which determined the grade were not in a position to influence the strength to any marked degree.

This lack of agreement between the grade and the test data has often led to the erroneous conclusion that the theories back of the grade were in error. Fig 4 (*f*), however, shows the results of applying the theory as closely as it is thought will ever be practicable. This figure also shows that when the theory is closely followed, the rules give almost perfect segregation of the timbers in so far as their control of the influence of defects on the strength is concerned. The rules which give the results shown in Fig. 4 (*f*) would require considerable refinement in grading and would require the use of branding or other methods to insure timbers being placed with the best side down. In general, Fig. 4 shows what might be expected from a segregation of timbers by each of the three methods. It shows that the injury from defects increases with seasoning, and that the efficiency of the rules should not be judged by the results of tests on green material. It also demonstrates the correctness of the theory on which the rules are based.

DISCUSSION

Mr. Nolan. MR. THOMAS NOLAN.[1]—I should like to know what the tests show in regard to the effect of spiral grain on the compressive strength and other properties of wooden columns and wooden beams.

Mr. Newlin. MR. J. A. NEWLIN.—The exact law for loss of strength due to spiral or diagonal grain has not been established. We find an appreciable decrease in strength due to cross-grain alone, which in the tensile strength starts at a slope of about 1 in 40, in bending at about 1 in 25, but in compression the spiral or diagonal grain does not appreciably decrease the strength until the slope is about 1 in 12. Even when the effect of cross-grain on the strength is not appreciable, its presence is not desirable because as the timbers dry out the spiral twists tighter and timbers will not stay straight. When the checking which accompanies drying occurs, it, of course, follows the spiral grain and increases the injury resulting from cross-grain. On the lower side of a beam, this increased injury from checking is about two or three times the original injury. It is for these reasons that we limit cross-grain and spiral grain in the best grade of timbers to a slope of 1 in 15, although when tested green they probably will not show a material loss until the cross-grain has a slope of about 1 in 10. It is when timbers dry out, and checking has had a chance to develop, that we find a marked weakness from cross-grain.

Mr. Nolan. MR. NOLAN.—In regard to knots in beams and girders in horizontal shear: do they increase the resistance to that shear? One would naturally think they might, as in the somewhat analogous resistance of keys in a keyed beam. Or do knots decrease resistance to horizontal shear?

Mr. Newlin. MR. NEWLIN.—They do not increase the resistance to shear very much, since the grain runs around the knot. However, when you have a clear piece the checks are usually straight and continuous but when knots are present there will be an offset of an inch or two between checks. This wood between the checks fails by tension or compression rather than shear. Thus the knots tend to increase shear strength by decreasing the injury from checks, but do not as a rule run in the right direction to key the pieces.

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[1] Professor, Department of Architecture, University of Pennsylvania.

MR. NOLAN.—I should like to ask another question that is interesting to architects. Have you been able to determine the cause of shakes in timber, or is this one of the questions not yet definitely decided? **Mr. Nolan.**

MR. NEWLIN.—That is a question that has been before us for a good many years, and one that I should like someone to answer. They used to say that they were caused by wind. The objection to this theory is that they frequently occur in trees which have been protected from the wind and they do not occur in the portion of the tree where the largest shear stresses are developed. From the standpoint of mechanics I can not see how the wind can ever form them. There is also a theory that they are the result of some kind of fungous action. While there is no certainty as to their cause, it is known that they do occur in the living tree and do not result from drying unless there is a weakness in the bond between the rings at the time of cutting. It is checks that form in drying. **Mr. Newlin.**

TENSION TESTS OF THIN GAGE METALS AND LIGHT ALLOYS

By Harvey A. Anderson[1]

In attempting to improve the methods used in testing materials for parts of telephone apparatus, it has been found that machines and practices are not as well developed for tension tests of thin sheets, foil and fine wires as in the case of plate and cast materials. Large quantities of flat contact carrying springs made of thin gage alloy strips less than 0.050 in. thick, and of helical springs of music wire are used in telephone apparatus. In order that telephone exchanges may operate efficiently, it is necessary that the apparatus shall be very compact. Such space limitations frequently necessitate the design of springs to operate at stresses close to the elastic limit, and ordinary factors of safety applied to the ultimate strength are inadequate.

Accurate tension tests with stress-strain measurements of the elastic properties of these spring materials must be made in order to obtain the information required for design and specification purposes. The loads involved in making such tests are small, and particularly so in the case of thin gage light alloys which are gradually coming into use in communication engineering.

Telephone Apparatus Material Tests

The choice of materials for telephone apparatus is usually preceded by extensive investigations of their physical and chemical properties and of their performance under service conditions of exaggerated severity. These tests frequently include determinations of the elastic and strength properties, of the hardness, ductility, resistance to suddenly applied and repeated loads, and of resistance to corrosion, as well as of the machining qualities and other manufacturing characteristics. In order to satisfactorily resist corrosion, the materials must be selected largely from the available non-ferrous alloys. For flat springs, phosphor bronze and nickel silver are most generally employed but occasionally brass is used.

Tension testing of thin gage metals and alloys is of importance to a number of industries, and particularly to aircraft and communication engineers. Although the standardized practices of the

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[1] Bell Telephone Laboratories, Inc., New York City.

A.S.T.M. are of considerable assistance in the development of laboratory technique for such tests, it has been found necessary in some instances to develop new apparatus and methods of testing.

Determinations of the elastic properties of thin specimens have necessitated the use of precision micrometers with 0.0001-in. graduations and the development of new forms of extensometers capable of being mounted on thin sheet and fine wire samples, Fig. 1. In addition, it has been found necessary to increase the accuracy of the lever and pendulum type testing machines. A new type of self-aligning jaws has been developed for tension tests of thin sheet material to avoid eccentric stressing.

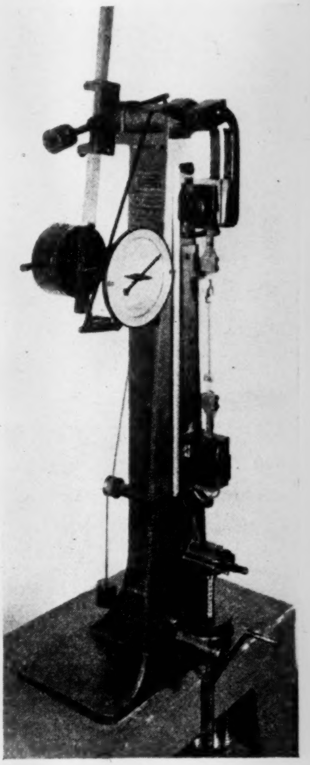

FIG. 1.

DEVELOPMENT OF SHEET TENSION TEST SPECIMEN

Test specimens should be so designed as to give results representative of the material from which they have been selected. Certain sizes and shapes of test specimens are recommended in the Appendix to the 1923 Report of the Society's Committee E-1 on Methods of Testing,[1] for plate material and for other material. However, the discussion of the report brings out the fact that no agreement has been reached on standard specimens for sheet material. Considerable development work has been done in the Bell System Laboratories to determine a satisfactory form of specimen for sheet material which would not be subject to complex stresses, and in which the fracture would occur in the middle third of the gage length. Practically all of this work has been on material less than 0.050 in. thick, and the conclusions below apply particularly to such sheet material.

The most commonly used test specimen for all purposes is one with a gage length of 2 in. It is preferable then, in the absence of other controlling factors, to determine the elongation in a 2-in. gage length to permit of comparisons with the work of other laboratories.

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[1] *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part I, p. 495 (1923).

However, the earlier recommendations of Committee E-1[1] are quite definite in recommending that strain measurements for the determination of the modulus of elasticity shall be made in a gage length of not less than 8 in. to secure greater accuracy in calculations of unit strain. In the matter of gage length of specimens this has resulted in the adoption of somewhat over 8 in. for the standard length of reduced section wherever the available stock permits. Gage points (very light prick punch marks) are made on the specimen each inch for the eight inches and one inch beyond on each end. The elongation is then measured after fracture over the 2 in. in which the break is located most centrally.

The width of sheet specimens is commonly made $\frac{1}{2}$ in. as being in accordance with general practice and affording a reasonable mean between a specimen which would be too narrow to be representative of the sheet and one which would be so wide as to be likely to tear in the test.

The two factors which required experimental work to determine the best solution were the widths of the ends and the radii of the fillets connecting the ends to the reduced section. Fig. 1 of the Appendix to the 1923 report of Committee E-1[2] recommends for plate material a specimen with ends "$1\frac{1}{3}$ *b*" wide where "*b*" is the width of the reduced section. This results in the use of a specimen with ends $\frac{2}{3}$ in. wide where the reduced section is $\frac{1}{2}$ in. wide. A specimen with ends $\frac{21}{32}$ in. wide and with $\frac{3}{4}$-in. radius fillets at the juncture of the ends and the 2- or 8-in. reduced section was tried first. The width of the reduced section of all specimens is tapered to 0.001 in., minimum, to 0.003 in., maximum, undersize at the middle to localize the fracture.

The specimen described above was found to give fairly satisfactory results in tests of ductile sheet materials such as aluminum and zinc. However, in a series of tests of 8-per-cent tin phosphor bronze it was found that the fracture occurred almost invariably about $\frac{1}{8}$ in. from the fillet, or shoulder, using a specimen with a 2-in. gage length. An attempt was first made to relieve the stress concentration at this point by using a 3-in. radius fillet in place of the $\frac{3}{4}$-in. radius, but without success. The widths of the ends were then reduced from $\frac{21}{32}$ in. to 0.55 in. or from about $1\frac{1}{3}$ *b* to $1\frac{1}{10}$ *b*, and it was found that this gave fractures in the middle of the gage length regardless of whether the specimens had $\frac{3}{4}$ or 3-in. radius fillets or 2 or 8-in. gage lengths. The 3-in. radius fillet has been adopted as being on the safer side.

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[1] 1921 Book of A.S.T.M. Standards, p. 841.

[2] *Loc. cit.*

The stress concentrations resulting from abrupt changes in cross-section have been studied extensively by E. G. Coker of the University of London using transparent celluloid specimens and polarized light.[1] He found that a reduction of width from about 2 *b* to *b* with 0.3-in. radius fillets gave a stress concentration near the shoulders 20 per cent greater than the stress intensity at the middle of the reduced section. A similar specimen with $\frac{1}{16}$-in. radius fillets showed a 58 per cent increase of stress near the shoulders. He says further that "In every case where variations of normal stress occur at a cross-section, they are accompanied by cross stress and shear which at some points have considerable intensity. The slightly variable stress intensity was found to disappear when the enlarged ends had a breadth (only) about 13 per cent greater than that of the gage length." He confirmed the findings of other experimenters that specimens in which the reduced section is merely a semi-circular groove give abnormally high strength values, as reported by Martens, Kirkaldy and Moore.[2] Coker also recommends that the length of the reduced section with parallel sides shall be somewhat greater than the effective gage length to avoid stress concentrations within the gage length.

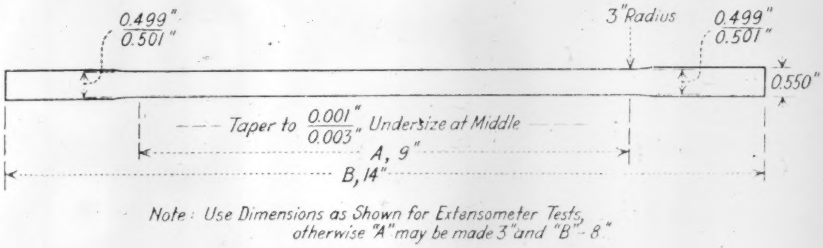
0.499"
0.501"
3" Radius
0.499"
0.501"
0.550"
Taper to 0.001" / 0.003" Undersize at Middle
A, 9"
B, 14"
Note: Use Dimensions as Shown for Extensometer Tests, otherwise "A" may be made 3" and "B" - 8"

FIG. 2.—Tension Test Specimen.

RECOMMENDED SHEET TENSION TEST SPECIMEN

Following the indications of the above-mentioned studies, a tension test specimen having the dimensions shown in Fig. 2 has been selected as a tentative standard for tests including stress-strain measurements on sheet metals. Where it is impracticable to make the specimen of this length, or when it is desired to determine only the strength and elongation, the over-all length may be reduced from

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[1] *General Electric Review*, Vol 24, p. 82, January, 1921.

[2] *Proceedings*, Am. Soc. Testing Mats., Vol. XVIII, Part I, p. 417 (1918).

14 to 8 in. with a 3-in. reduced section (instead of 9 in.) and the other dimensions as in Fig. 2.

Specimens are sheared out rectangular and then milled to the dimensions given in Fig. 2, using a light tool cut to bring to size. The approximate 0.002-in. reduction at the center is obtained with a fine carborundum stone. The cross-section is measured at the middle which is the point of minimum area if the sheet gage is sufficiently uniform.

ACCURACY STANDARDS IN TENSION TESTS

The determination of the true elastic properties of materials requires that each of the operations involved in determining the proportional limit and modulus of elasticity shall be carried out accurately. These include preparing the test specimen, measuring the dimensions at the reduced cross-section and making simultaneous determinations of the loads and elongations during the test with an accurate testing machine and extensometer. All measurements involved in the test must be carried out at least within the percentage error which is claimed for the proportional (elastic) limit (*P*-limit) and the modulus of elasticity determined.

It should be borne in mind that an error of 0.0001 in. in the measurement of the thickness of a 0.050-in. sheet specimen introduces the same percentage error in the value found for the area as does an error of 0.001 in. in the measurement of a 0.500-in. width. For this reason it has been found desirable to make all measurements on thicknesses of sheet material with a "barrel type" micrometer reading directly to 0.0001 in. and permitting estimations of 0.00001 in. For thicknesses as small as 0.002 in. this instrument substantially meets the recommendation in Paragraph 6 of the Appendix to the Report of Committee E-1[1] specifying the use of a micrometer reading to $\frac{1}{200}$ of the dimension measured.

The run of sheet material tested in the Bell System Laboratories averages 0.020 in. thick (No. 24 B. & S. gage). For a specimen of that thickness, $\frac{1}{2}$ in. in width, the error must not exceed ± 0.25 per cent in measurements of width and thickness to insure an error less than ± 0.5 per cent in the computed area of cross-section. The actual dimensions of the specimen are always used in computing unit stresses rather than the nominal dimensions given in Fig. 2.

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[1] *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part I, p. 496 (1923).

CALIBRATION OF TESTING MACHINES

The laboratory equipment includes a "Universal" lever type testing machine of 10,000-lb. capacity, and a pendulum type machine of 600-lb. capacity. Calibrations are made about every 6 months by dead weights throughout the range of the 600-lb. machine and up to 2000 lb. on the larger machine, as this covers the range required for tests of most sheet and wire specimens encountered. The standard weights used are in 50-lb. units and are periodically certified by the Bureau of Weights and Measures of the City of New York to an accuracy of $\pm\frac{1}{4}$ oz. When these weights are loaded on the testing machines, the beam or pointer should register the applied load with an error not greater than $\pm\frac{1}{4}$ lb. up to 1200 lb. and ± 1 lb. for higher proof loads. Suitable adjustments are made to the poises, when required, in order to obtain this accuracy. This accuracy of ± 0.05 per cent for the lower range (that is, at 500 lb.) is probably only obtainable in a machine located in a research laboratory, and falls off slightly due to wear and tear between calibrations. Under ordinary operating conditions, readings of loads for stress-strain and modulus determinations, with the testing machine pulling head moving at a

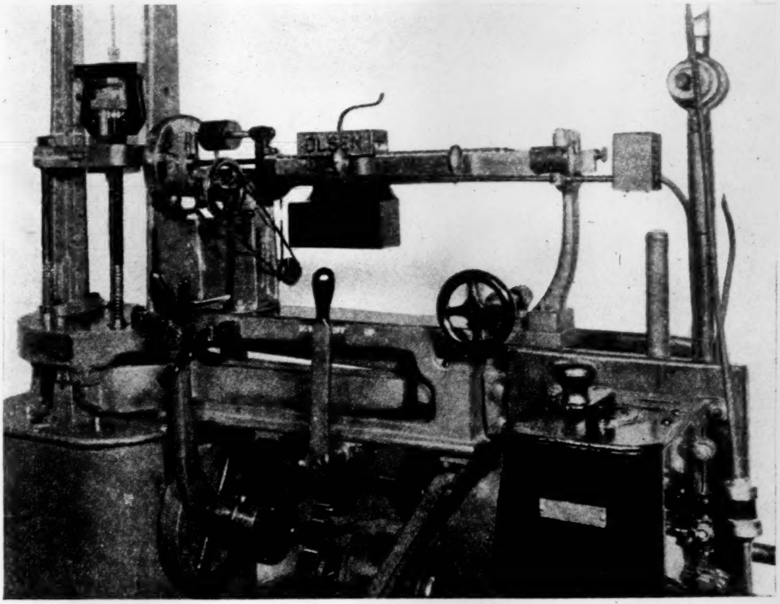

FIG. 3.—Testing Machine Equipped with Optical Projection Apparatus.

speed of approximately 0.02 in. per minute, are obtained with an allowable error of not to exceed ±0.5 per cent. Determinations of breaking loads up to 1200 lb. are made well within a maximum error of ±0.25 per cent, including observational errors as well as machine errors.

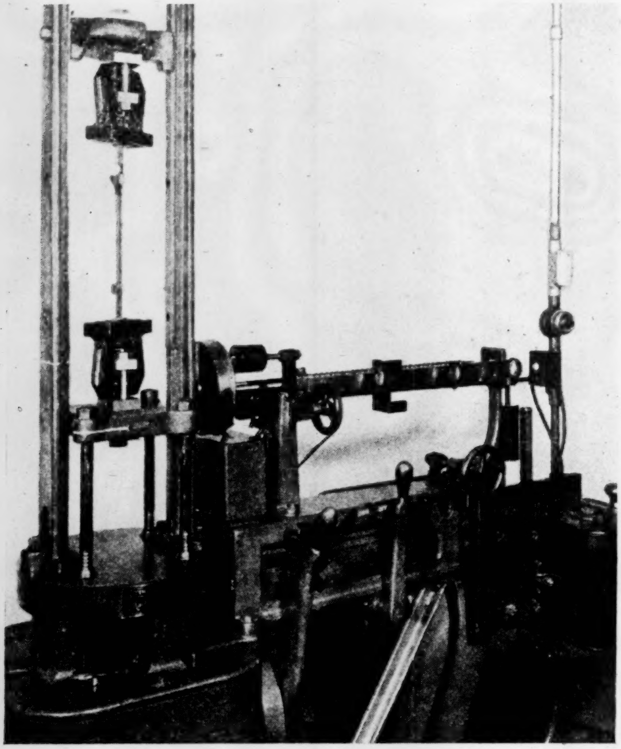

FIG. 4.—Machine Equipped with Self-Aligning Jaws.

OPTICAL PROJECTION OF BEAM POSITION ON SCALE

A modification in the Universal type lever machine which has facilitated obtaining accurate load readings is a means of projecting the position of the beam on to the load scale, Fig. 3. This is accomplished by means of an index pointer attached to the fore end of the beam which moves in front of a source of light and a frame indicating the central beam position. A suitable condensing and resolving lens system mounted on the framework supporting the beam projects an actual size image of the pointer and index on the circular dial carrying the load scale. This brings the specimen, the position of the beam and the load reading all within easy observation of the operator.

SELF-ALIGNING TENSION TEST JAWS

Experience in the Bell System Laboratories confirms the conclusion in Batson and Hyde's "Mechanical Testing," page 74, that as much care is necessary in the design of the grips for holding the specimens as in any of the other essential parts of the testing machine if accurate results are required. It was found in the case of both our lever and pendulum type machines that the specimen will be stressed eccentrically unless the jaws are aligned with great care and the machine is in excellent adjustment. The eccentric stresses are a serious source of error in tests of very thin sheet material. A set of self-aligning jaws and holders (Fig. 4) has been constructed embodying features of the various designs illustrated in the Appendix to the 1923 report of Committee E-1. The jaw holders are suspended on ball bearings similar to the "Robertson axial loading shackles for tension" (Batson and Hyde, page 79). One of the jaws in both the top and bottom pairs has a ball-and-socket bearing on the back which automatically compensates for differences in thickness of the specimen ends.

Very satisfactory results have been obtained in tests with these jaws, and the previous tendency for thin specimens to tear is no longer observed. Consideration was given to the novel design of pneumatic jaws developed by N. S. Otey and used at the Naval Aircraft Factory, Philadelphia,[1] but it was felt that his design was unsuited for our use.

A simple type of self-aligning jaws consisting of a pair of plates bolted together and loosely suspended is used for tests of very thin sheet material (Fig. 1). These latter jaws operate satisfactorily up to loads of about 200 lb.

LIGHT-DIAL TYPE EXTENSOMETER

The determination of the proportional limit and modulus of elasticity of sheet and wire material involves taking readings of the loads and of the corresponding elongations with an accurate extensometer. Since no extensometer of the required accuracy suitable for mounting on thin specimens was commercially available, it was found necessary to develop one. For the indicating device of such an extensometer, the small "Last Word" dial (manufactured by H. A. Lowe, Cleveland, Ohio) was selected because of its light weight and high degree of accuracy as shown by calibration tests at the U. S. Bureau of Standards. The actuating mechanism of this dial consists of a multiplying lever, the short arm of which is attached to the work to be measured, while the tip of the long arm engages a helical thread on the shaft on which the pointer is mounted. Clamps were devised to be attached to the specimens with point supports at either end of the gage length so that the extensometer is entirely supported on a thin specimen and is not touched during the test.

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[1] N. S. Otey, "Tension Testing of Thin Plate Metals," *Iron Age*, p. 1008, March 27, 1924.

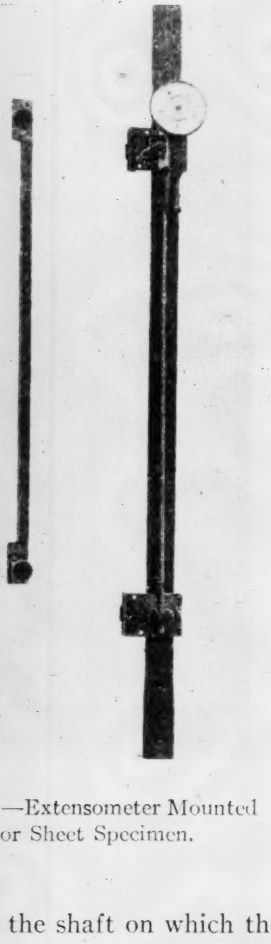

FIG. 5.—Extensometer Mounted or Sheet Specimen.

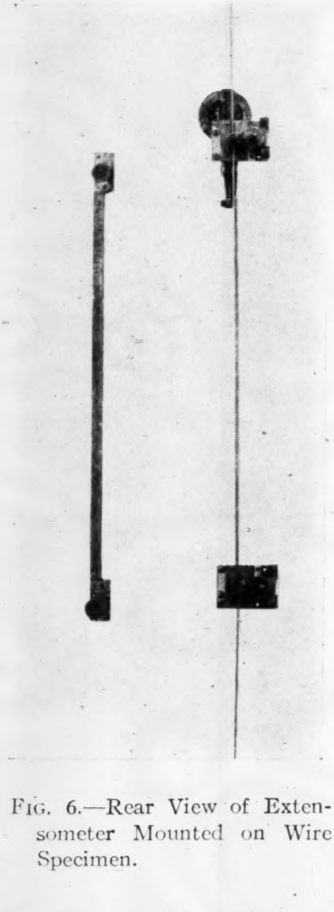

FIG. 6.—Rear View of Extensometer Mounted on Wire Specimen.

Fig. 5 shows the complete "Last Word" extensometer mounted on a sheet specimen, and Fig. 6 is a rear view of the same extensometer as mounted on a wire specimen. The Last Word dial, alone, weighs 1.1 oz., and the 8-in. extensometer complete weighs a total of 2.2 oz., excluding the weight of the space bar which is removed after the extensometer is mounted. The dial is attached rigidly to the upper clamp of the extensometer. A connecting rod with a cross-pin is hooked in the short end of the multiplying lever of the dial, and this rod is secured to the lower clamp by a set screw. The extensometer is assembled with a space bar with pins fitting in the upper and lower clamps to obtain the 8-in. gage length between the locating points. In practice the specimen is first mounted in the testing machine and a small load applied. The extensometer is then attached by tightening the nuts bearing on the clamp arms carrying the upper and lower locating points. The space bar is removed, the set screw securing the connecting bar is tightened and the test run off taking simultaneous observations of the loads and the extensometer readings.

The accuracy attainable with this extensometer for a typical case can be illustrated by a test of 0.020-in. thick 8-per-cent tin phosphor bronze sheet specimen of the dimensions shown in Fig. 2. This material has a modulus of elasticity of about 14,500,000 lb. per sq. in. and a *P*-limit of about 65,000 lb. per sq. in. in spring temper. The total extension in 8 in. at the *P*-limit for this material is $8 \times \frac{65{,}000}{14{,}500{,}000}$ or 0.036 in. A minimum of ten readings to the proportional limit is taken in order to accurately determine the slope of the straight line and the point of divergence of the curve. With the Last Word extensometer reading to 0.001 in. with an accuracy of at least ± 0.0002 in. over the range of the dial (0.040 in.), this insures the desired accuracy of ± 0.5 per cent in the extension determinations, consistent with the accuracy in measurements of the cross-section and applied loads. This percentage accuracy is maintained throughout the computation of unit stresses and strains, the plotting of the stress-strain curve and the determination of the proportional limit and the modulus of elasticity.

ADVANTAGES AND USES OF LIGHT ALLOYS.

Refinements in Bell System tension testing apparatus and methods have been necessitated to a considerable extent by the increasing use of light metals and alloys. Light alloys merit consideration wherever weight is a determining factor in construction. The two chief groups of light alloys are those with aluminum and those with magnesium as the base. The mechanical properties of these alloys can be improved by heat treatment and cold working, but of the two, magnesium alloys are decidedly more cold short. Among the light alloys the best known is duralumin, containing about 95 per cent aluminum, 4 per cent copper and small percentages of manganese, magnesium, silicon and iron. Duralumin has a specific gravity of only 2.8 and can be heat treated and cold rolled to have a tensile strength as high as 80,000 lb. per sq. in. Its most notable use has been in the construction of Zeppelins and other aircraft.

The most widely known magnesium alloys are the electron metals containing upwards of 90 per cent of magnesium with variable percentages of aluminum, zinc, manganese and copper. They have found their chief field of application in the construction of automobile and airplane pistons where their high thermal conductivity and light weight combined with moderately high tensile strength and elongation have given them certain marked advantages over aluminum and cast iron. One heat-treated and cold-worked electron alloy has a tensile strength of 48,000 lb. per sq. in. with a specific gravity of only 1.8.

TABLE I.—TENSILE PROPERTIES OF DURALUMIN PLATE AND SHEET.

Line	Supplier	Thickness, in.	Treatment (see Note 2)	Proportional Limit, lb. per sq. in.	Strength, lb. per sq. in.	Elongation in 2 in., per cent
1	A	0.622	T	43 000	68 200	11.0
2	A	0.030	TR	37 500	76 500	4.5
3	A	0.021	TR	38 300	64 200	10.5
4	A	0.017	TR	31 800	57 300	17.0
5	B	0.015	TR	......	72 800	3.7
6	B	0.0019	TRC	......	83 300	0.8
7	A	0.0017	TRC	......	80 000	0.5

NOTE 1.—Average modulus of elasticity, 10,000,000 lb. per sq. in.
NOTE 2.—T, heat treated; R, cold rolled; C, aged 40 hours at 100° C.

The advantages which have made aluminum and magnesium alloys superior for aircraft and piston construction have also made them superior for many other uses such as the moving parts in textile machinery, for optical instruments, artificial limbs and fan blades. When an extensive development of radio apparatus necessitated the use of improved materials in parts for transmitting and reproducing speech vibrations, consideration was given to the use of these light alloys. Both aluminum and magnesium alloys have been successfully used.

TENSILE DATA ON LIGHT ALLOYS

Table I contains some results of tests on duralumin sheet material. These properties, in general, correspond fairly well with those reported by Hoyt in "Metallography—Metals and Common Alloys;" Grard in "Aluminum and Its Alloys;" Merica in U. S. Bureau of Standards *Bulletin No. 76*, "Aluminum and Its Light Alloys;" and Bach and

Baumann in "Konstruktions—Materialien." No published results of tests of sheet material as high as 80,000 lb. per sq. in. have come to the writer's attention, except figures reported by Albert Sauveur while a representative of the U. S. National Advisory Committee for Aëronautics, at Paris, during the World War. It is apparent from the table that this strength may be obtained from either of the two manufacturers' materials by sufficient cold working after heat treatment.

The published information on tension test results of magnesium alloys, including electron metals, is less extensive than on aluminum alloys. Table II contains certain data obtained in our laboratory for magnesium alloys together with the manufacturers' test results on other experimental lots of material of approximately the same composition.

TABLE II.—RESULTS OF TESTS ON MAGNESIUM ALLOYS.

Line	Alloys	Tested by	Thickness, in.	Form of Samples	Specific Gravity	Proportional Limit, lb. per sq. in.	Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent
	AMERICAN MAGNESIUM ALLOYS								
1	Mg 100	B.S.L.	0.016	Rolled	....	8 000	26 600	14.8	....
2	Mg 100	A.M.C.	.....	Rolled	1.74	2 500	25 000	4.0	5.0
3	Mg 96, Al 4	B.S.L.	0.012	Rolled	....	10 500	33 600	14.8	....
4	Mg 96, Al 4	A.M.C.	.....	Rolled	1.77	7 500	41 000	8.5	10.0
5	Mg 95, Al 4, Mn 1	B.S.L.	0.012	Rolled	....	11 500	28 600	5.2	....
	ELECTRON METALS								
1	"Z1", Mg 95, Zn 5, Cu trace	B.S.L.	0.500	Extruded	1.82	13 300	39 500	22.3	29.5
2	"Z1", Mg 95, Zn 5, Cu trace	E.M.C.	.....	Extruded	1.81	9 000	38 500	19.0	24.0
3	"Z1", Mg 95, Zn 5, Cu trace	Moore	.....	Extruded	1.78	6 260	36 500	17.5	20.5
4	"AZM", Mg 91, Al 5, Zn. 3, Mn. 1	B.S.L.	0.500	Extruded	1.75	13 500	49 200	....	16.7
5	"V1", Mg 90, Al 10, Cu trace	B.S.L.	0.500	Extruded	1.82	10 900	47 500	13.0	12.2
6	"V1", Mg 90, Al 10, Cu trace	E.M.C.	.....	Extruded	1.83	24 000	50 000	11.0	14.0
7	"E" (heat treated)	B.S.L.	0.500	Extruded	....	13 900	44 000	17.8	....

NOTE 1.—Modulus of elasticity (pure magnesium and high magnesium alloys), 6,250,000 lb. per sq. in.
NOTE 2.—"B.S.L."—results from tests in Bell System Laboratories, New York.
NOTE 3.—"A.M.C."—results from "Magnesium," Handbook of American Magnesium Corporation (1923).
NOTE 4.—"E.M.C."—results from correspondence, Elektron Metals Corporation of America (1923).
NOTE 5.—R. R. Moore, "Resistance of Manganese Bronze, Duralumin and Electron Metal to Alternating Stresses," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 110 (1923).

The use of magnesium alloys is practically in its infancy in this country, although considerable use has been made of the electron metals in Germany. The high strength-weight and resilience-weight ratios of these alloys, combined with their high thermal conductivity and easy machineability, would seem to compensate somewhat for the necessity of protecting the surface against corrosion. The increased volume of material compared with the same weight of other alloys justifies their use on economic grounds in certain cases. A serious drawback in the use of these alloys for some purposes is the rapid hardening with cold work. However, at a temperature around 350° C., magnesium is quite plastic and it may be rolled, spun or drawn without hardening.

COMPARATIVE STRENGTH AND RESILIENCE FACTORS

The two mechanical properties of these light alloys that are of the greatest interest to the designer are the modulus of elasticity as a measure of the stiffness of the material and the strength or maximum load-carrying capacity. H. C. Knerr has suggested[1] that the relative advantages of various materials, for uses where the weight is of prime importance, may be expressed conveniently by a strength-weight factor obtained by dividing the strength in thousands of pounds per square inch by the unit weight or specific gravity. Using the strengths and weights given above, duralumin has a strength-weight factor of about 28.5 and electron of about 26 as compared with factors of 7.5 for mild steel, 35 for Swedish spring steel and 12 to 14 for phosphor bronze and 18-per-cent nickel silver.

TABLE III.—COMPARISON OF TENSILE PROPERTIES OF SHEET MATERIAL—SPRING TEMPER (EXCEPT AS NOTED).

Line	Material	Specific Gravity	Proportional Limit, lb. per sq. in.	Strength, lb. per sq. in.	Elongation in 2 in., per cent	Modulus of Elasticity, lb. per sq. in.	Quality Factors[a]	
							Strength / Weight	Resilience / Weight
1	Mild Carbon Steel	7.85	35 000	60 000	30.0	30 000 000	7.6	2.6
2	Swedish Spring Steel	7.85	150 000[c]	275 000	1.2	30 000 000	35.1	47.8
3	Monel Metal, Ni 67, Cu 28, Fe, etc.	8.95	90 000	125 000	3.5	25 400 000	14.0	17.7
4	Phosphor Bronze "A", Cu 96, Sn 4, P trace	8.60	55 000	120 000	0.7	16 000 000	14.0	11.0
5	Phosphor Bronze "C", Cu 92, Sn 8, P trace	8.55	70 000	115 000	2.5	14 500 000	13.4	19.8
6	Nickel Silver "B", Cu 56, Zn 26, Ni 18	8.50	55 000	105 000	1.0	20 000 000	12.4	8.9
7	Brass "A", Cu 65, Zn 35	8.50	60 000	100 000	2.2	14 500 000	11.8	14.6
8	Duralumin, Al 95, Cu 4.5, Mg, etc.	2.80	50 000	80 000	0.8	10 000 000	28.6	44.6
9	Electron V1, Mg 90, Al 10[b]	1.85	11 000	47 500	13.0	6 250 000	25.7	52.4
10	Mg 96, Al 4[b]	1.80	10 500	33 500	17.0	6 250 000	18.6	49.0

Majority of above results from tests in Bell System Laboratories, New York City.

[a] For derivation of quality factors, see preceding pages.

[b] Annealed Material. Results for spring temper not available.

[c] Interpolated from test results on strength and from Bureau of Standards *Circular No. 101.*

For spring design where the maximum energy content of the spring is of major importance, it is suggested that a more useful static quality factor is obtained by taking the ratio of the elastic resilience of the material to its specific gravity. This elastic resilience is approximately equal to the energy which can be stored in the material without permanently deforming it and can all be subsequently recovered. It is represented graphically by the area under the stress-strain curve up to the proportional limit. The resilience-weight ratio is equal to one-half the product of the stress and the strain at the proportional limit divided by the specific gravity, or, it is numerically equal to the square of the stress at the proportional limit divided by twice the product of the modulus of elasticity and the specific gravity. Duralumin has a modulus of 10,000,000 lb. per sq. in. and electron of about 6,250,000 lb. per sq. in. On the basis of the data given in Table III for spring temper sheet materials, duralumin has a resilience-weight ratio of about 44.5, electron 52.5, mild steel 2.5, Swedish spring steel 48, and nickel silver and phosphor bronze about 10 to 20.

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[1] H. C. Knerr, "Material Selection Should be Based on Strength-Weight Factors," *Automotive Industries*, p 868, April 19, 1923.

Where spring stiffness is of major importance, of course the modulus of elasticity of the material is the deciding factor, but the choice must be made among materials with the required elastic strength. Since the moduli of elasticity of the light alloys are lower than for most alloys, they do not compare favorably with steel or copper alloy springs of equal thickness. However, lower modulus or more flexible alloys of slightly greater thickness may often be used in place of the usual spring materials with a saving in weight, since the stiffness of a beam varies as the third power of the thickness, but only as the first power of the modulus of elasticity.

COMPARISON OF NON-FERROUS ALLOYS AND STEELS

In conclusion, a comparison between the light alloys and certain other sheet materials will assist in determining which material to use in a specific case where questions of cost, availability and tendency to corrode do not govern the choice. Table III shows such a comparison.

DISCUSSION

Mr. Marshall.

MR. C. H. MARSHALL[1] (*presented in written form*).—The author of this paper has rendered testing engineers in general a service by calling attention to the necessity of improvements in the testing machines, etc., for the tension testing of thin gage materials. In our experience, neither a 10,000-lb. capacity lever type testing machine nor a 600-lb. capacity pendulum type machine, however carefully calibrated, will be satisfactory for material of the thinness discussed. A 500-lb. capacity lever type testing machine and a 50-lb. capacity pendulum type machine, calibrated to an accuracy of $\frac{1}{4}$ oz. or better, would be more suitable for such accurate work. Due to the fact that manufacturers of testing apparatus in the United States have not given their attention to a suitable type of machine for testing thin sheet material and very fine wires, the average laboratory has been compelled to resort to dead-load when tests of this kind were received. The American Steel and Wire Co., of Worcester, Mass., has in use a large number of very accurate hydraulic testing machines of small capacity and great accuracy. These machines are of their design and are supplemented by self-aligning jaws designed after the pattern of the parallel rule. The physical testing laboratory of the General Electric Co., Schenectady, N. Y., has designed a similar machine for testing thin gage metals and fine wire. In Europe, Schopper and other makers of testing apparatus have perfected very satisfactory machines for this class of work.

Reference to the special form of test piece in order to prevent tearing might be supplemented by emphasizing the importance of careful machine work in the preparation of samples. Where a number of samples are prepared at one time, they can be clamped together and milled longitudinally. Transverse milling is liable to introduce irregularities in the width of the specimen. Where very large numbers of specimens are tested, a die should be provided for stamping the test pieces from the sheet material. It is very doubtful whether the resilience, weight and other factors given for such light aluminum alloys would be satisfactory data for designing engineers of springs to enable them to judge of the value of these materials for various uses. The extended practical experience with these alloys or the addition of data on their fatigue value will probably also be required.

Mr. Quick.

MR. G. W. QUICK[2] (*presented in written form*).—Mr. Anderson's paper will be of great interest to all those who have occasion to make

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[1] Testing Engineer, Chemical and Physical Testing Laboratory, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

[2] Associate Physicist, U. S. Bureau of Standards, Washington, D. C.

Mr. Quick. tests of quality on thin sheet metal, particularly when the elastic properties are of prime importance. As the author states, there is a comparative dearth of published information on preferred methods for making tension tests of thin gage metal, and for this reason such information as the quantitative data given on the effect of ratio of the width of ends to the width of reduced section and the radius of fillet on stress concentration as well as methods for measuring the elastic properties of thin sheet material are valuable in design of test specimens, and should lend added weight to results obtained in this way.

We have been carrying out at the U. S. Bureau of Standards, a series of tests to determine the relative rolling characteristics of open-hearth deep-drawing stock and electrolytic iron. Samples cut after each pass through the rolls were used for test purposes including among others tension and bend tests.

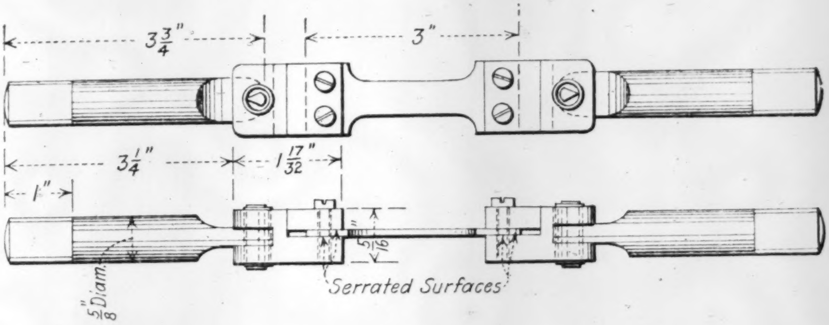

Fig. 1.—Adapter for Gripping Thin Sheet Tension Test Specimen.

I wish to call attention to a special type of grip which was designed and made at the Bureau to obtain uniform loading over the entire cross-section of the specimen. These grips, which are a modification of those suggested by Mr. C. A. White, are shown in Fig. 1. The threaded ends screw into the fixtures of the testing machine which are hung from spherical seats.

Another special type of apparatus for testing thin sheet metal developed at the Bureau by S. C. Petrenko is for a bend test. In this test the specimen is caused to bend around a radius equal to 15 times its thickness while under a tensile stress of 4000 lb. per sq. in. Fig. 2 shows a side elevation of this bend test apparatus and Fig. 3 shows a specimen during test.

Rolls of different diameters may be placed in the steel frame and held in position by the sliding wedges and thumb screw. The specimen is hung free from a clamp which rests on the rolls. The

Mr. Quick. frame is first turned upward through 90 deg. about the farther roll as an axis and then brought back to the horizontal position and through 90 deg. about the nearer roll to the vertical position and then back to the horizontal.

Fig. 4 shows the results of bend tests on specimens of open-hearth and electrolytic steel taken both longitudinally and transversely, in which the number of complete cycles causing failure are plotted as ordinates and the percentage of reduction in thickness, by cold rolling, as abscissas.

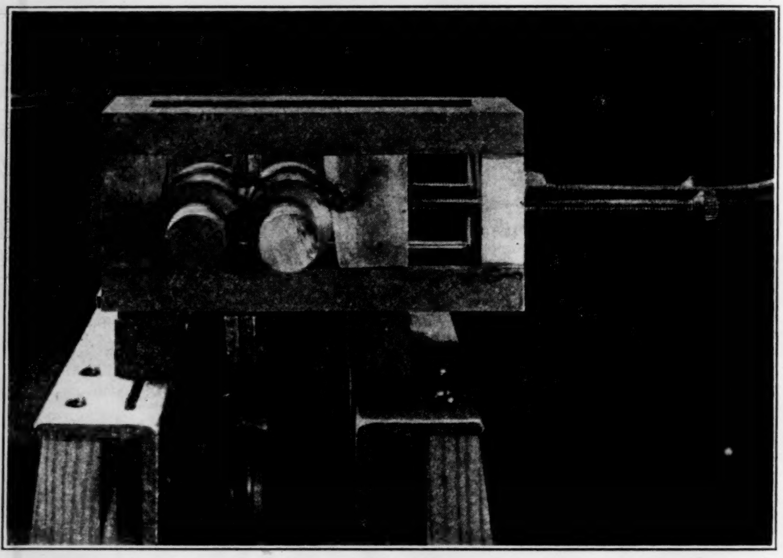

FIG. 2.—Side View of Bend Test Apparatus.

The results obtained by this method are somewhat erratic but in general seem to bring out some characteristics of the material. The method offers means for a simple qualitative test, and merits consideration by those interested in tests on thin sheet metal.

Mr. Whittemore. MR. H. L. WHITTEMORE[1] (*presented in written form*).—In our laboratory at the U. S. Bureau of Standards, we have tested few specimens of thin sheet metal and, therefore, have not devoted the study to this important subject that it has received from Mr. H. A. Anderson at the Western Electric Co., Mr. R. L. Templin at the Aluminum Co. of America, and Mr. N. S. Otey at the Naval Aircraft Factory. In each of these laboratories the properties of the material are measured with a high degree of precision and other laboratories can study the methods which they have developed with great profit. **Mr. Whittemore.**

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[1] Mechanical Engineer, U. S. Bureau of Standards, Washington, D. C.

In view of the large number of tests which are described nowadays for materials, it is interesting to note the importance that is attached to the tension test, or "pulling test," the test that has been the main reliance of materials engineers since they began to get numerical values for the properties that measure quality. Although many of the materials are used for springs, no fatigue test is specified. Although music wire is used for helical springs, the inference is that tension tests give the information needed to judge the torsional properties.

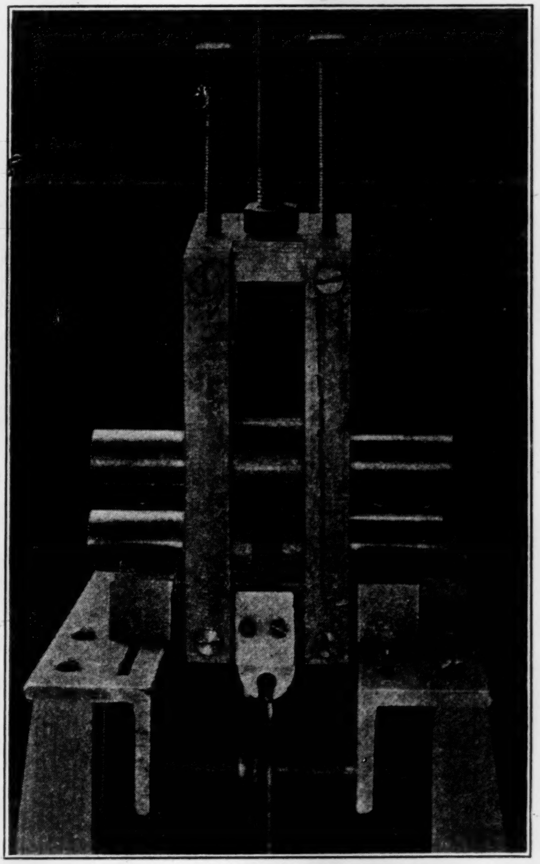

FIG. 3.—Front View of Bend Test Apparatus.

The combination of the advantages of the 8-in. gage length specimen with those of the 2-in. specimen is very ingenious and could be applied

Mr. Whittemore. to cylindrical specimens having a diameter of ½-in. The discovery that making the ends of the specimen narrower reduced the stress at the fillet and caused the specimen to break near the middle is a remarkable illustration of the practical application of Coker's photoelastic work.

The extensometer which is very carefully worked out in its details, is apparently as accurate as any which could be used for these thin specimens, unless Tuckerman's optical strain gage is available. Unlike this strain gage, Mr. Anderson's extensometer is cheap, and simple. It has the disadvantage that deformations on one side only of the specimen are measured. Another last word dial micrometer could, perhaps, be placed on the opposite side of the specimen but the increased accuracy might not be appreciable as the specimen is comparatively long and the measuring mechanism very near the axis of the specimen.

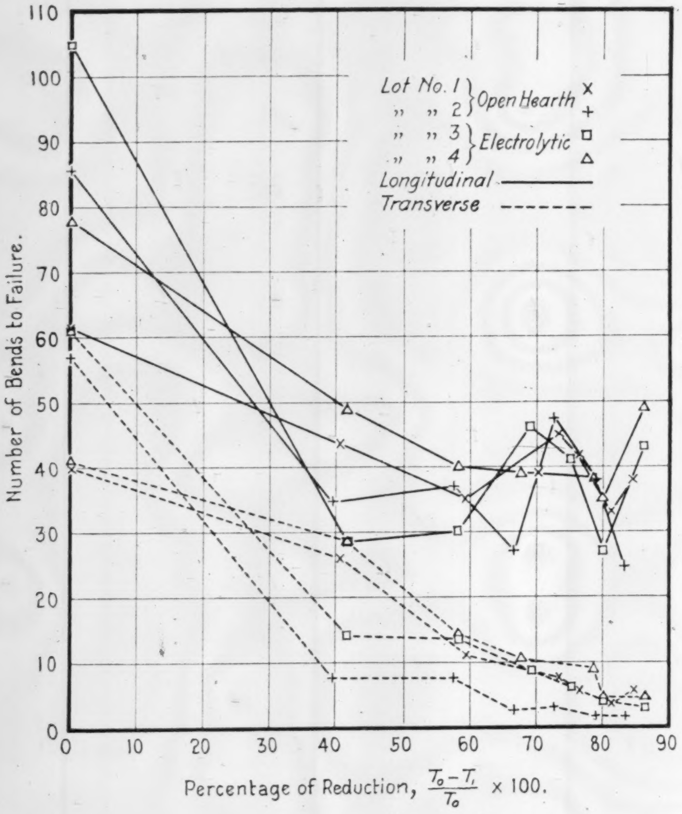

FIG. 4.—Results of Bend Tests.

Mr. Whittemore.

In Mr. Anderson's laboratory it is evident that the errors of the testing machines are known and care taken that they do not at any time exceed allowable values. This very commendable condition will in the next few years become the rule in laboratories rather than the exception.

The properties of the materials given in this paper are valuable for comparison. If all laboratories having test results of this kind would make them available for others, our knowledge of materials would increase more rapidly.

The value of Table V would be increased if the resilience for each of the materials were given in inch-pounds per cubic inch. These values may be computed from the data given in the table and are given here.

1.	Mild Carbon Steel	20.4
2.	Swedish Spring Steel	667.0
3.	Monel Metal	159
4.	Phosphor Bronze "A"	94.5
5.	Phosphor Bronze "C"	169
6.	Nickel Silver "B"	75.6
7.	Brass "A"	124
8.	Duralumin	125
9.	Electron V1	9.7
10.	Magnesium	8.81

It is evident that unless the saving of weight is of most vital importance, steel springs are the proper ones to use as they have been for ages. If resistance to corrosion is important, the steels and the magnesium must be eliminated and the remaining metals should be considered in the following order: bronze "C", monel metal, duralumin, brass "A", bronze "A".

It would be very interesting to know the relation of the working stresses used in designing telephonic apparatus to the proportional limit of the material. The reader gains the impression from this paper that the working stresses are at least equal to the proportional limit if not a bit above.

The practical selection of the allowable stress for parts, which like some springs are subjected to a few hundred thousand repetitions of stress, is also an engineering question of considerable importance. Obviously, the stress need not be as low as for parts subjected to several billion repetitions nor, apparently, should it exceed the proportional limit, but the best method of selection of a stress without experimental data for a guide is a problem which has puzzled many designers.

Mr. Petrenko.

MR. S. N. PETRENKO[1] (*presented in written form*).—The importance of the development of proper apparatus for tension testing of thin metals,

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[1] Associate Mechanical Engineer, U. S. Bureau of Standards, Washington, D. C.

Mr. Petrenko. particularly of light alloys is generally recognized and Mr. Anderson's work is a timely one. The results reported by the author with regard to the shape of the specimen are very interesting and valuable. It is to be regretted that no pictures showing the details of the apparatus which he uses are given.

In regard to the accuracy of the final results, I cannot agree that a uniform accuracy for all of the determinations will justify a claim for the same accuracy for the value of the proportional limit nor for the modulus of elasticity. As more than one quantity is measured, the accuracy of the final result will always be less than for any single determination.

Mr. Anderson. MR. H. A. ANDERSON (*Author's closure by letter*).—The comment of Mr. Marshall regarding the unsuitability of a 10,000-lb. lever type or a 600-lb. pendulum type machine for tests of sheet materials of very light gages (such as 0.002 in. thick) is entirely justified. The description of the testing machines in the paper did not cover all testing machines in the laboratories with which the author is associated, but was only intended to apply to testing machines on which modifications have been made in our laboratories in an attempt to improve the performance over that of stock machines.

A Schopper pendulum type machine of 100-lb. capacity with $\frac{1}{4}$-lb. graduations and having a second scale with 20-lb. capacity graduated in 0.1 lb. has been found very satisfactory for the determination of strengths and elongations of duralumin and magnesium alloy foil less than 0.002 in. thick.

The comment of Mr. Marshall regarding the necessity for longitudinal milling of tension test specimens is well taken and is generally observed in the Bell Telephone Laboratories. However, for alloy foil less than 0.002 in. thick the most satisfactory method of preparing specimens has been found to be by using a template accurately dimensioned to the sizes of the standard tension test specimen shown in Fig. 2 of the paper. The foil is cut out with a sharp pointed knife with the material lying flat on a surface plate.

The importance of the bend test requirement in specifications for sheet materials is emphasized by Mr. Quick. We have found that one of the big advantages of this method consists in showing up the relatively poor forming qualities of sheet materials where the line of bend corresponds approximately to the direction of rolling of the sheet. Elongation values of specimens cut with their length at right angles to the direction of rolling may show higher elongations than specimens cut with their length parallel to the direction of rolling. In the former case the elongation represents a tearing apart of the "fibers" of the sheet and is not accompanied by proportional necking in or

Mr. Anderson.

reduction of area. Inasmuch as reduction of area determinations are difficult on thin sheet materials, repeated bend test requirements are to be preferred because they are much easier to carry out and yield comparable information regarding the ductility.

Mr. Whittemore comments on the lack of emphasis on fatigue tests for spring materials in telephone apparatus. This lack of emphasis is due to the fact that present-day fatigue tests on non-ferrous alloys are practically as time consuming as service tests of apparatus. The inapplicability of the Gough short-time deflection test for determining an endurance limit for non-ferrous alloys was pointed out by Mr. L. B. Tuckerman at the annual meeting of the Society in 1923.[1]

Since the preparation of this paper there has been some evidence that a relation exists between the fatigue endurance limit of metals and the grain size. This may enable us to assure longer life for spring materials by the inclusion of standard micrographs indicating maximum allowable grain size in a manner analogous to that followed in the Tentative Specifications for Brass Condenser Tubes (B 55 - 24 T).[2]

The deduction that the working stress in certain springs of telephone apparatus under extreme conditions may approach the tensile proportional limit is in accordance with the facts. However, it should be borne in mind that the stress range involved is fairly small and may vary with safety from a minimum value slightly below the proportional limit to a maximum value approximately equal to the proportional limit. The use of such stresses, when required, is apparently in accord with the findings of fatigue investigators that the value of the endurance limit may occasionally exceed that of the proportional limit. Moore and Jasper report that "under cycles of stress, not involving complete reversals, the endurance limit is not infrequently found at unit stresses above the proportional elastic limit, and, consequently, the tendency is for the actual unit stress to be somewhat lower than the computed values."[3]

It is regretted that the extent of the drawings required for the construction of the new testing apparatus described in the paper makes it impractical to include the details as suggested by Mr. Petrenko.

The tenor of the foregoing discussions and the numerous other verbal comments of testing engineers interested in thin sheet metals would seem to indicate that there exists an urgent need for early standardization work by the American Society for Testing Materials in this field.

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[1] *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 128 (1923).

[2] *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part I, p. 797 (1924).

[3] "An Investigation of the Fatigue of Metals—Series of 1923," University of Illinois, Engineering Experiment Station, *Bulletin No. 142*, p. 71, May 26, 1924.

DETERMINATION OF POISSON'S RATIO AND A SUGGESTION FOR ITS USE IN STRESS ANALYSIS

By T. McLean Jasper[1]

This paper was written with a two-fold purpose in view: namely,

1. To compare the values for Poisson's ratio obtained by the use of the elastic constants with those obtained by direct measurement.
2. To outline a method of stress analysis by using Poisson's ratio, which can be applied directly to cases of design where ordinary methods of mathematical analysis are so complicated that the necessary assumptions preclude a surety of accuracy.

Poisson's Ratio by Direct Measurement and by the Use of the Elastic Constants

In the development of the mathematical theory of elasticity, a material is assumed which is homogeneous. If the assumption be also made that it is isotropic, the application of the theory becomes comparatively simple. Practically no material used in construction is homogeneous and isotropic in the strict sense. Many metals used where strength is of importance are assumed to be homogeneous and isotropic. How correct this assumption is might be surmised if values of Poisson's ratio obtained by direct measurement could be compared with values obtained by using the elastic constants in conjunction with the relations developed by the elastic theory. At least the lack of correlation might be a fair measure of the probable error involved in the use of the theory of elasticity provided sufficient sensitiveness and accuracy were obtained in the measuring apparatus.

Apparatus.—In measuring the values of the modulus of elasticity, a testing machine, sensitive to readings of 5 lb., and with an accuracy tolerance of about 0.2 per cent within the range covered, was used. The torsion testing machine had a comparable accuracy and sensitiveness. An extensometer of the Ewing type reading to 0.0002537 in. per inch of gage length per division of reading and a torsion indicator sensitive to 0.0000125 radian per division per inch of gage length, with each having an accuracy tolerance of about 0.2 per cent, were used in these experiments, also a lateral extensometer sensitive to readings of 0.000003 in. and with an accuracy tolerance of about 3 per cent within the range of these experiments.

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[1] Research Assistant Professor of Engineering Materials, University of Illinois, Urbana, Ill.

From the information given above and the applications which follow it will be readily seen that more accurate determinations of Poisson's ratio are likely to be obtained by using the elastic constants in connection with the formula:

$$\rho = \frac{E}{2F} - 1 \qquad (1)$$

where ρ represents Poisson's ratio, E the modulus of elasticity, and F the modulus of rigidity or shear, than can be expected by using the direct method of measurement with the lateral extensometer.

In the direct method of measuring Poisson's ratio

$$-\rho = \frac{\delta\, \epsilon_T}{\delta\, \epsilon_L} \qquad (2)$$

where ϵ_L represents the deformation per unit of length in the direction of the loading, and ϵ_T the deformation per unit of length transverse to the direction of loading. If the material is tested within the limit of proportionality, then

$$-\rho = \frac{\Delta\, \epsilon_T}{\Delta\, \epsilon_L} \qquad (3)$$

In calibrating the extensometer and the torsion indicator used, the same standard of length was adopted in each case, so as to eliminate as far as possible inaccuracies due to calibrating standards.

Materials.—The tests were designed primarily for wrought ferrous metals. It was thought wise to have the state of the material as nearly uniform as possible; therefore, with one exception, all ferrous materials tested were in a normalized condition. It is suggested that Poisson's ratio may vary with different conditions of a steel, and for this reason it is hoped that eventually a survey will be made of these various steels in the sorbitic and troostitic states as well. As wide a range of carbon content as could be found in the stock of known steels used in the Investigation of the Fatigue of Metals was used. The following list gives the chemical composition and treatments of the steels:

Steel	Chemical Composition, per cent							State of Metal
	C.	Cr.	Ni.	Si.	Mn.	P.	S.	
No. 9	0.02	....	....	0.02	0.03	0.005	0.042	Rolled
No. 10	0.69	....	....	0.12	0.46	0.017	0.029	Normalized
No. 6	0.93	....	....	0.03	0.38	0.017	0.045	Normalized
No. 1	1.20	....	....	0.19	0.25	0.021	0.021	Normalized
No. 7	0.41	0.18	3.41	0.25	0.75	0.020	0.020	Normalized
No. 5	0.24	0.87	3.33	0.15	0.37	0.019	0.025	Normalized

In addition to these steels, monel metal, electron metal, duralumin, manganese bronze, nickel-copper alloy, and Cyclops metal were tested, the composition and treatments of which are as follows:

Metal	Chemical Composition, per cent								State of Metal
	Cu.	Fe.	Si.	Zn.	Mn.	Al.	Sn.	Mg.	
Electron metal	0.41	0.25	0.24	4.38	....	trace	....	94.72	Rolled
Duralumin	3.25	0.28	0.28	....	trace	95.49	....	0.70	Rolled
Manganese bronze	56.85	1.50	....	40.90	0.20	0.23	0.23	....	Cast

Metal	Chemical Composition, per cent									State of Metal
	Mn.	Cr.	Fe.	Ni.	C.	Si.	S.	P.	Cu.	
Monel metal No. 111	1.51	26.66	2.50	69.00	0.20	0.053	0.0025	0.033	....	Rolled
Monel metal No. 112	1.55	29.83	1.88	65.87	0.14	0.02	....	....	....	Rolled
Copper-nickel alloy No. 113	....	....	0.16	19.43	....	....	....	....	80.03	
Cyclops metal No. 2	0.49	8.31	69.25	19.70	0.33	1.16	....	....	....	Rolled

Description of Tests and Specimens.—The specimens were made from stock which was found to be homogeneous, and the static properties of any one specimen of a material varied a very small percentage from the mean for that material.[1] The same specimens were used for the determination of the modulus of elasticity, for the determination of the modulus of rigidity, and for the direct measurement of Poisson's ratio. Care was taken to utilize only about one-half of the elastic range of the material.

The specimens consisted of bars 13 in. long and, with a few exceptions, $\frac{3}{4}$ in. in diameter. The gage length used, except for transverse strain measurements, was approximately 8 in.

Test Results.—The test results given in Table I are typical of those obtained for the specimens tested.

An average of ten double sets of readings was taken for each modulus and for each specimen. The results are summarized in Table II. It will be noticed from the results recorded in Table I that readings were taken at slightly different temperatures. Experimental and theoretical results are available which show that the moduli of elasticity and rigidity decrease as the temperature increases. Separate investigations by Sutherland[2] and the author[3] indicate the rate of change of these elastic constants for wrought ferrous metals, for temperatures up to 750° F. (400° C.).[4]

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[1] See reports of Investigation of the Fatigue of Metals, *Bulletins*, 1922–1923, University of Illinois, and R. R. Moore, "Resistance of Manganese Bronze, Duralumin, and Electron Metal to Alternating Stresses," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 106 (1923).

[2] W. Sutherland, "Kinetic Theory of Solids," *Phil. Mag.*, 1891.

[3] T. M. Jasper, "Value of the Energy Relations in Testing of Material," *Phil. Mag.*, October, 1923.

[4] The formula used by the author is taken from Sutherland's work, with certain modifications which are developed in the author's article.

TABLE I.—MODULUS OF RIGIDITY, MODULUS OF ELASTICITY AND POISSON'S RATIO

MODULUS OF RIGIDITY

Steel No. 10; Specimen No. 10 A46C; 0.49 per cent Carbon; Normalized; Gage Length, 7.865 in.; Diameter, 0.749 in.

Temperature, deg. Cent.	Moment Reading, P	Stress, lb. per sq. in.	Angle of Twist		Modulus of Rigidity, F, lb. per sq. in.
			Reading	Radians	
23.8	2.5	0	.....	....	.....
23.6	9.1	800	37.4	0	.....
23.6	62.1	7320	149.0	0.01116	12 270 000
23.6	8.0	666	34.3	0	.....
23.5	63.6	7410	151.1	0.01168	12 280 000
23.5	8.0	666	34.3	0	.....
23.5	63.5	7400	151.1	0.01168	12 260 000
23.5	6.6	796	32.0	0	.....
23.5	62.9	7320	150.6	0.01860	12 220 000

MODULUS OF ELASTICITY AND POISSON'S RATIO

Steel No. 10; Specimen No. 10 A44C; 0.49 per cent Carbon; Normalized; Gage Length, 7.99 in.; Diameter, 0.769 in.; Gage factor, $\frac{8}{7.99}$.

Temperature, deg. Cent.	Load, lb.	Stress, lb. per sq. in.	Longitudinal Strain		Transverse Strain		Modulus of Elasticity, E, lb. per sq. in.	Poisson's Ratio, ρ
			Reading	in. per inch	Reading	in. per inch		
20.0	1135	2 570	71.3	0	0.3738	0	....	
20.0	6780	15 400	87.9	0.000421	0.3823	0.000099	30 480 000	0.236
20.0	1280	2 910	71.9	0	0.3742	0	....	
20.0	6780	15 400	87.9	0.000406	0.3823	0.000096	30 760 000	0.232
20.0	1280	2 900	71.9	0	0.3742	0	....	
20.0	6950	15 750	88.2	0.000414	0.3829	0.000100	31 040 000	0.246
20.0	1375	3 120	72.0	0	0.3744	0	....	
20.0	6920	15 700	88.2	0.000411	0.3826	0.000110	30 610 000	0.233

TABLE II.—SUMMARY OF RESULTS OF TESTS ON WROUGHT FERROUS METALS FOR THE MODULUS OF RIGIDITY, ELASTICITY, AND POISSON'S RATIO

Steel	Description	Modulus of Rigidity, F			Modulus of Elasticity, E			Poisson's Ratio, ρ		
		Temperature of Test, deg. Fahr.	F, lb. per sq. in.	F, Corrected to 60° F., lb. per sq. in.	Temperature of Test, deg. Fahr.	E, lb. per sq. in.	E, Corrected to 60° F., lb. per sq. in.	Temperature of Test, deg. Fahr.	ρ	ρ corrected to 60° F.
No. 9.	0.02-per-cent Carbon	74.3	12 600 000	12 630 000	68.9	29 890 000	30 020 000	68.9	0.194	0.197
No 10.	0.49-per-cent Carbon	74.4	12 260 000	12 290 000	69.0	30 500 000	30 610 000	68.0	0.238	0.241
No. 6.	0.90-per-cent Carbon	70.7	12 000 000	12 020 000	77.9	29 660 000	29 870 000	77.9	0.235	0.241
No. 1.	1.20-per-cent Carbon	81.5	12 040 000	12 050 000	78.8	29 660 000	29 880 000	78.8	0.254	0.260
No. 7.	3.5-per-cent Nickel Alloy	81.5	11 950 000	11 990 000	67.8	30 310 000	30 410 000	77.0	0.259	0.265
No. 5.	Cr. Ni. Alloy	79.7	11 760 000	11 780 000	74.3	29 630 000	29 830 000	74.3	0.256	0.261

Table II gives the results for the modulus of rigidity, for the modulus of elasticity, and for the direct measurement of Poisson's ratio for the wrought ferrous metals. Table III shows the final comparison of the values of Poisson's ratio obtained by both methods, adjusted for a temperature of 60° F. (16° C.).

It is suggested that Poisson's ratio values calculated from the elastic constants are more consistent than those obtained by the direct method. This was explained in the early part of this paper by reference to the percentage accuracy of the lateral extensometer when considering the gage lengths and measurements used in getting the moduli. The values of Poisson's ratio for normalized carbon steels are in very close agreement. For the steel in the "as-rolled" condition it is apparent that the values are lower than for the normalized steels. No explanation is offered at this time for this fact. Further experiments are suggested investigating the effect of orientation of the metal in the rolls during the process of manufacture, the rate of cooling, and other factors. The two normalized alloy steels have similar compositions with the exception that the chromium-nickel steel has a lower percentage of chromium and the 3.5-per-cent-nickel steel a larger percentage of carbon. Values of Poisson's ratio for these steels are in close agreement.

TABLE III.—SUMMARY OF RESULTS FOR POISSON'S RATIO MEASURED DIRECTLY, AND CALCULATED FROM THE ELASTIC CONSTANTS AND ADJUSTED FOR A TEMPERATURE OF 60° F.

Steel	Description	Poisson's Ratio, ρ		Condition of Steel
		By Direct Measurement	Calculated from Elastic Constants	
No. 9	0.02-per-cent Carbon	0.197	0.188	As rolled
No. 10	0.41-per-cent Carbon	0.241	0.245	Normalized
No. 6	0.90-per-cent Carbon	0.241	0.243	Normalized
No. 1	1.20-per-cent Carbon	0.260	0.241	Normalized
No. 7	3.5-per-cent Ni. Alloy	0.265	0.268	Normalized
No. 5	Cr. Ni. Alloy	0.261	0.267	Normalized

The main point to be brought out at this time is the close agreement between values of Poisson's ratio obtained by calculation using the moduli of elasticity and rigidity and those obtained by direct measurement. In the latter part of this paper an outline will be given of a method of using the direct method of measurement in the analysis of stress distribution.

The values of Poisson's ratio obtained for non-ferrous metals were not reduced to a temperature basis of 60° F., but care was taken that the tests were performed at temperatures which varied only a very few degrees. The average temperatures at which the tests were made are recorded and this will allow corrections for a selected standard temperature at any future time. In most of the tests the temperature was the same for each set. The estimated variation of Poisson's ratio for a temperature variation from 0 to 100° F. is given in Table V for a normalized 0.49-per-cent-carbon steel. This is done to give some idea of the probable variation of Poisson's ratio with varying temperature.

Table IV shows the summary of results of determinations of Poisson's ratio for non-ferrous metals.

TABLE IV.—SUMMARY OF RESULTS OF TESTS ON NON-FERROUS METALS

Metal	Condition of Metal	Modulus of Rigidity, F, lb. per sq. in.	Modulus of Elasticity, E, lb. per sq. in.	Poisson's Ratio, ρ	Temperature of Tests, deg. Fahr.
Monel Metal No. 111	Rolled	10 340 000	25 930 000	0.253	80.3
Monel Metal No. 112	Rolled	10 190 000	25 670 000	0.259	79.2
Copper-Nickel Alloy	......	7 440 000	20 480 000	0.375	80.6
Manganese Bronze	Cast	5 348 000	13 970 000	0.306	82.0
Electron Metal	Rolled	2 523 000	6 358 000	0.260	83.3
Duralumin	Rolled	3 946 000	10 060 000	0.275	81.5
Cyclops Metal	Rolled	11 130 000	26 580 000	0.191	80.6

TABLE V.—ESTIMATED VARIATION OF POISSON'S RATIO FOR A TEMPERATURE VARIATION FROM 0 TO 100° F. FOR A 0.49-PER-CENT-CARBON STEEL NORMALIZED

Temperature, deg. Fahr.	Modulus of Elasticity, lb. per sq. in.	Modulus of Rigidity, lb. per sq. in.	Poisson's Ratio, ρ
0	31 320 000	12 350 000	0.267
20	31 080 000	12 330 000	0.260
40	30 840 000	12 310 000	0.253
60	30 610 000	12 290 000	0.245
80	30 360 000	12 260 000	0.238
100	30 120 000	12 230 000	0.231

General Conclusions.—In the results given for ferrous metals it will be noticed that the values of Poisson's ratio are lower for the "as-rolled" materials than for the normalized steels. This fact was noticed independently from a study of the elastic constants obtained for duralumin.

There is every reason for supposing that very accurate values of Poisson's ratio may be determined from the elastic constants The direct method of measuring this ratio has been applied to non-ferrous metals with results similar to those obtained for steel. If the elastic theory holds for metals within the elastic limit, and it seems that it does, it is very evident that Poisson's ratio can never be greater than 0.5 nor less than zero, provided an isotropic material is used.

It would be of interest to measure the value of Poisson's ratio above the elastic limit of a material in order to apply the results to stress analysis above the elastic limit, and for this reason it is planned to perform the necessary experiments in the near future.

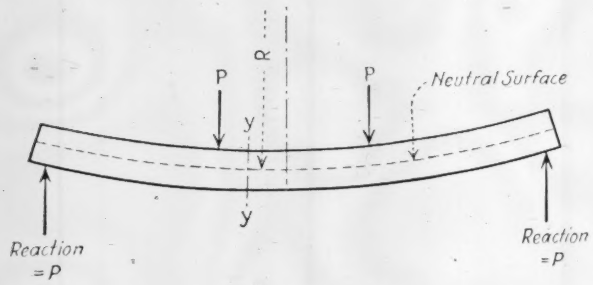
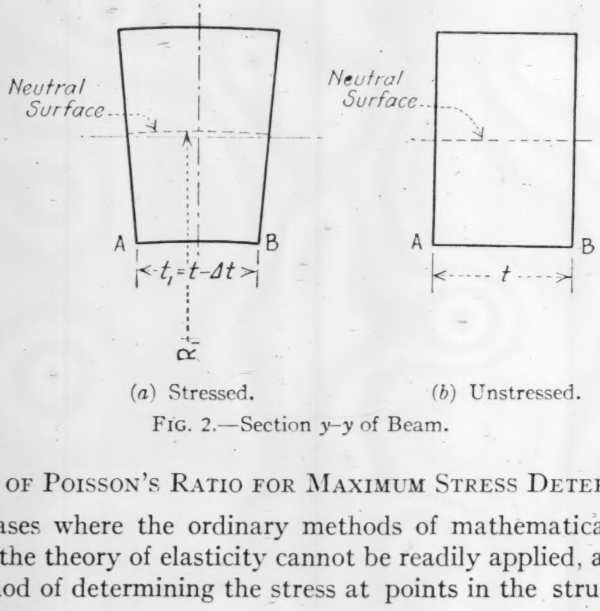


FIG. 1.—Diagram of Beam Under Simple Bending.



(a) Stressed. (b) Unstressed.

FIG. 2.—Section y–y of Beam.

THE USE OF POISSON'S RATIO FOR MAXIMUM STRESS DETERMINATION

In cases where the ordinary methods of mathematical analysis based on the theory of elasticity cannot be readily applied, an alternative method of determining the stress at points in the structure is of great importance.

We may consider the simple case of a rectangular beam made of an elastic isotropic material and loaded as shown in Fig. 1. The stressed section y–y will assume a shape similar to Fig. 2 (*a*). The maximum stress in this section will always be found at a discontinuity and will be associated with boundary conditions. Fig. 2 (*b*) represents the shape of the section y–y unstressed. By referring to the figure, it is seen that t represents the thickness of the beam unstressed, and t_1 the thickness of the beam stressed, in which case t–t_1 represents the change of thickness, or Δt. This Δt is caused, if the stress is not above the limit of proportionality of the materials, by a factor due to Poisson's ratio effect and a factor due to the curvature of the surface $A\ B$. In the case of a stiff material, such as steel, this curvature is found to be exceedingly small and its effect on the change of thickness may be neglected without materially affecting the accuracy of the results. The chief factor contributing to Δt, therefore, is the Poisson's ratio effect.

The foregoing discussion is applicable to relatively narrow members and precludes broad, thin, flat slabs.[1]

With the preceding discussion in mind, and assuming that the contribution to Δt by the curvature of the surface AB is less than 0.1 per cent of the total, the use of Poisson's ratio in determining the stress can be readily outlined.

From the above assumption and the mathematical theory of elasticity

$$\frac{\Delta t}{t} = \Delta \epsilon_T \ldots\ldots\ldots\ldots (4)$$

if Poisson's ratio, ρ and $\Delta\epsilon_T$ are known, substituting in Eq. 3 will give

$$\Delta \epsilon_L = -\frac{\Delta\epsilon_T}{\rho} \ldots\ldots\ldots\ldots (5)$$

The relation between the average stress over the boundary surface AB, Fig. 2, and $\Delta\ \epsilon_L$ can be shown to be

$$\Delta \epsilon_L = \frac{\Delta S}{E} \ldots\ldots\ldots\ldots (6)$$

or the increment of stress divided by the modulus of elasticity is equal to the change per unit of length in the direction of the stress. This is not true, however, excepting for boundary conditions.

Substituting in Eqs. 5 and 6

$$\Delta S = \frac{-\Delta \epsilon_T E}{\rho} \ldots\ldots\ldots\ldots (7)$$

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[1] For further discussion see "Strength of Materials," by Arthur Morely, 1920 Edition, pp. 236–237; "Mathematical Theory of Elasticity," by A. E. Love, 1920 Edition, pp. 127–131.

If the initial loading is zero, then within the limit of proportionality of the material

$$S = \frac{-\epsilon\tau E}{\rho} \quad \text{(8)}$$

This relation has been developed for a relatively simple case. It is true, however, for all cases in which loading causes bending without twisting and can be applied to peculiar shapes in which the methods of mathematical analysis are difficult to apply directly. In the case where the unit strain in the direction of the stress is continually changing, this method of stress analysis can be applied with considerable success, provided a sensitive lateral extensometer is available.

The conclusions to be drawn from the experiments are that the mathematical theory of elasticity is a very reliable means for stress analysis in wrought ferrous metals, and that failing a possibility of a direct application of the mathematical theory of elasticity the use of Poisson's ratio in conjunction with the moduli of elasticity and rigidity gives accurate values for stress analysis at points of maximum stress for members of peculiar shape. It should be pointed out, however, that the application of Poisson's ratio to stress analysis has its limitations and that its use simply allows accurate stress determination in a broader sense than is possible in the application of the mathematical theory of elasticity alone.

DISCUSSION

Mr. L. B. Tuckerman.[1]—The measurement of Poisson's ratio is one of those very important and rather difficult measurements which we all want to make and rarely do make, and Mr. Jasper is to be congratulated for his success in getting some very useful results. I am wondering, however, whether the value of it in stress analysis will be quite as great as Mr. Jasper thinks. In the case of varying stresses along a specimen, we find that, although our ordinary Euler-Bernoulli theory neglects the shear deformations, within the limits of the application of Poisson's ratio to determine a transverse deformation, shear deformation is sufficiently important that the lateral deformation at any one point represents not the longitudinal stress at that particular point but an average over the longitudinal stresses at neighboring points. I think that probably we would find that the lateral deformation would represent more closely the stress at that point than the average over a 2-in. gage length, but nevertheless the stresses so measured are not stresses at that point but the average over a certain length.

Mr. Tuckerman.

Mr. T. McL. Jasper (*Author's closure by letter*).—I am very grateful for the remarks of Mr. Tuckerman because they bring out a point which should be clearly understood in using Poisson's ratio for stress analysis. In the paper it is stated that this method can only be used for boundary conditions. Perhaps it would be more clear if it were stated that it is only true for edge conditions, considering the edges at the maximum distance on either side of the neutral surface.

Mr. Jasper.

In presenting this paper on Poisson's ratio the primary desire was to show that the values obtained in the ordinary manner could be used in stress analysis, providing sufficiently accurate extensometers were used. Methods of stress analysis for simple shapes are very well developed, but in cases where more complicated shapes are used the usual analysis is often considerably in error. The amount of this error depends largely on the assumptions made in the analysis and may also depend considerably on the physical and elastic properties of the materials used in the construction.

In the development of the "Mathematical Theory of Elasticity," assumptions are usually made that the materials considered are

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[1] Engineer Physicist, U. S. Bureau of Standards, Washington, D. C.

Mr. Jasper. isotropic, and that no portions of them are raised above the elastic limit. For such materials the differential equations are readily set up but in order to solve those equations complicated calculations are necessary in any but the most simple cases.

The main value of this paper therefore is in the evaluating, for several materials, the assumption of isotropy, and to suggest the possibility of the use of Poisson's ratio in determining the constants necessary for the solution of the differential equation mentioned above. It is suggested that the value of Poisson's ratio obtained by using the elastic moduli *E* and *F*, compared with the value obtained by direct measurement, will show how nearly isotropic the various materials are.

There is nothing new in the method of direct measurement of Poisson's ratio but as far as the writer knows the precautions necessary for testing the mathematical theory experimentally as applied to metals, have not heretofore been made. Mesnager the elastician first suggested the use of Poisson's ratio for stress analysis.

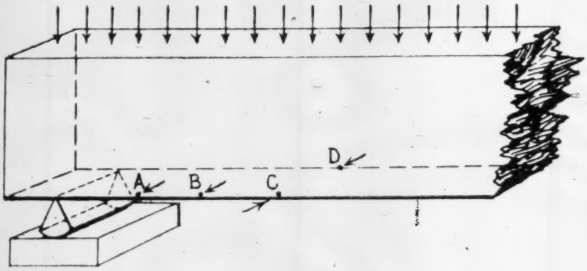

FIG. 1

From the experiments contained in the paper it is very clearly brought out that, statistically, steels and many other metals act as isotropic substances. In fact, however, it is known that these metals are a collection of crystals and when the elementary volume is considered they are not isotropic. This raises an important question which it is hoped will eventually be solved. Can we use a truly isotropic substance such as glass, together with polarized light, and expect the stress analysis so obtained to represent the stress distribution in a crystalin substance in actual practice? Certain experiments in fatigue would suggest that possibly this can not be done. In this case the elementary volume assumes greater importance. It is hoped that the percentage deviation in the two cases can be determined within reasonable limits. Until the suggested correlation between strictly isotropic materials and the statistically isotropic mate-

Mr. Jasper.

rials are made, full reliance cannot be placed on analysis using isotropic transparent media and polarized light.

By using Poisson's ratio obtained for a material the maximum stress values existing in the same material can be found for any particular shape in which it is used.

Great strides have been made in stress analysis in the past few years. In the accompanying Fig. 1, the first attempt at direct measurement is outlined and the more accurate use of Poisson's ratio is also outlined. By measuring the increment of strain between points *A* and *B* and using the modulus of elasticity the average stress between *A* and *B* can be obtained. By measuring the increment of strain between points *C* and *D* and using Poisson's ratio the stress at the point *C* can be obtained. In the case where the stress does not vary from the average between *A* and *B*, the first method is satisfactory but on the other hand when the stress varies from point to point the second method becomes by far the more accurate of the two.

DIRECT MEASUREMENT OF POISSON'S RATIO FOR CONCRETE

By A. N. Johnson[1]

As the result of cooperative work between the State Roads Commission of Maryland, the U. S. Bureau of Public Roads and the University of Maryland, a study of samples of concrete taken from the Maryland State highway system was undertaken at the engineering laboratory of the University.

The samples were cylindrical cores bored from the road by a drill specially made for this purpose. It was intended to study not only the breaking strength of the concrete samples, but also their elastic properties. For this purpose, there was used to determine the stress-strain curve a type of compressometer that may be called the five-point compressometer, as it clamps the specimen at five points.[2]

After considerable experience with this type of compressometer, somewhat modified in details from that used at the Lewis Institute, a number of observations were made with a simple arrangement of the Marten's mirror compressometer. A diagrammatic sketch of a test specimen with the mirror compressometer attached and the geometric relations involved are given in Fig. 1. The results with the latter were so divergent from those obtained with the five-point compressometer that further comparisons were made with other types of clamp compressometers and the mirror type. Typical results of these comparisons are shown in Fig. 2.

The curves *A*, *B*, *C* and *E* are comparisons with one of the clamp types; *D* with another type, and *F* with the five-point compressometer. It is to be observed that in all of the clamp types there is a distinct lag in the curve. The marked characteristic of the curves obtained upon all concrete specimens with the mirror compressometers was the straight-line relation for the portion of the curve from zero loading to elastic limit or limit of proportionality, whereas with the clamp types of compressometers such straight-line relation was not observed. The stress-strain curves in each series of this figure, except curves *F*, were made simultaneously with both types of compressometer attached to the specimen.

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[1] Dean, College of Engineering, University of Maryland, College Park, Md.

[2] Described by Stanton Walker, in *Bulletin No. 5*, Structural Materials Research Laboratory, Lewis Institute; also in the *Proceedings*, Am. Soc. Testing Mats., Vol. XIX, Part II, p. 510 (1919).

The fact that the clamp-type compressometer did not yield data that exhibited a straight-line relation for the stress-strain curve would lead to variable determinations for the modulus of elasticity for a given specimen, depending at which point of the curve a tangent was drawn.[1] It would, therefore, follow that the ratio of deformation at right angles to the line of pressure with the deformation parallel to the line of pressure—that is, Poisson's ratio—would vary according to the point of the stress-strain curve at which this ratio would be determined. But if the stress-strain curve for longitudinal deformations seemed to be a straight line, as observed with the mirror compressometer, there was a probability that lateral deformation would likewise be a straight line, in which case Poisson's ratio for a given specimen would be constant within certain limits. It was for the purpose of determining this relation that there were undertaken some direct measurements of the lateral deformation of concrete under pressure.

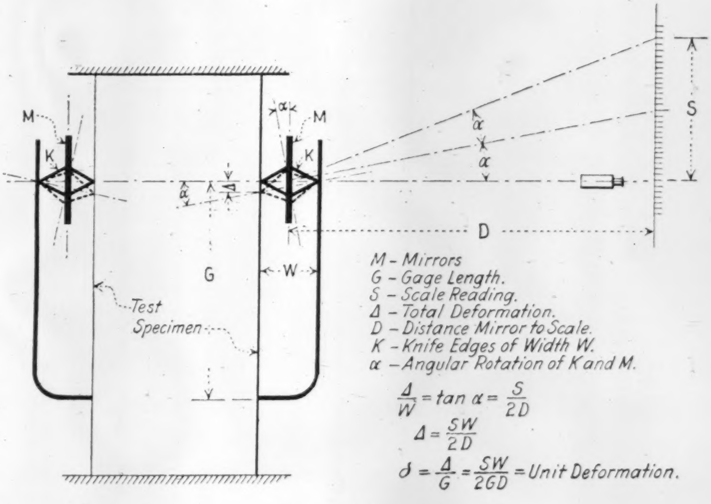
M
K
α
M
K
α
α
S
D
G
W
Test Specimen
M - Mirrors
G - Gage Length.
S - Scale Reading.
Δ - Total Deformation.
D - Distance Mirror to Scale.
K - Knife Edges of Width W.
α - Angular Rotation of K and M.
$\frac{\Delta}{W} = \tan\alpha = \frac{S}{2D}$
$\Delta = \frac{SW}{2D}$
$\delta = \frac{\Delta}{G} = \frac{SW}{2GD}$ = Unit Deformation.

FIG. 1.—Diagrammatic Sketch of Mirror Compressometer.

In order to measure accurately the small lateral deformations that occur, a comparatively simple apparatus was devised.

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[1] Stanton Walker, "Modulus of Elasticity of Concrete," *Bulletin No. 5*, Structural Maerialst Research Laboratory, Lewis Institute, Chicago, Ill. (January, 1920); *Proceedings*, Am. Soc. Testing Mats., Vol. XIX, Part II, p. 510 (1919).

DESCRIPTION OF APPARATUS FOR DETERMINING POISSON'S RATIO

The apparatus is illustrated diagrammatically in Fig. 3, while Fig. 4 is a view of the apparatus as set up. The specimens, which are cylindrical and approximately 9 in. high and 4½ in. in diameter, were mounted in the testing machine with a spherical bearing block at the top. Two aluminum rings, each surrounding the specimen, have points of contact with the cylinder on diametrically opposite sides. The rings are separated by two rollers or rods, and on one end of each is mounted a mirror. Thus, increase in the diameter of the concrete cylinder would cause a movement of the rings over one another, which would cause a rotation of the rollers and thus angular movement of the mirrors.

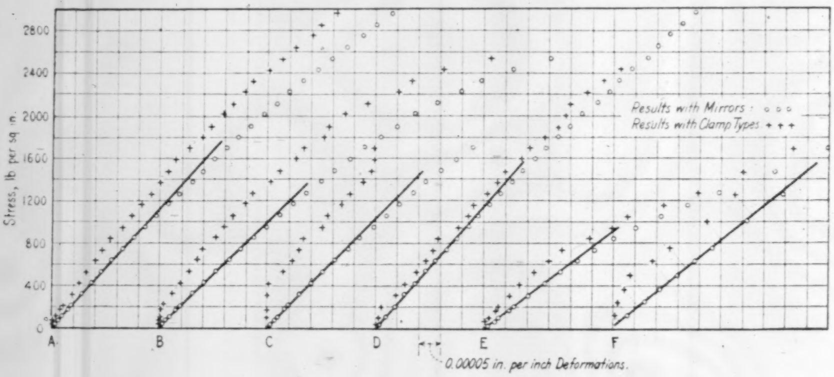

FIG. 2.—Comparison of Compression-Deformation Curves for Concrete Obtained with Various Types of Set-Screw Clamp and Micrometer-Dial Compressometers, with Mirror or Optical Lever Compressometer. Tests Made Upon Cylindrical Specimens.

In using the mirror compressometer, in order to compensate for any movement of the specimen as a whole, or any movement of the weighing table upon which the specimen rests, with reference to the scales which are reflected in the mirrors, it is necessary that the movement producing the deformation, which it is desired to measure by the rotation of the mirrors, shall be indicated by two mirrors diametrically opposite each other and so arranged that the rotation of the one mirror is in opposite direction to the rotation of the other. Thus, if there is any movement of the specimen as a whole causing movement of the mirrors, the scale reading of the one will be as much increased as the scale reading on the other is decreased. Therefore, when the readings are averaged, any error that would be caused in the observations due to such movement of the specimen becomes zero. For this reason it was necessary so to arrange the rings that as the diameter of the specimen increased under pressure, thus moving the rings apart, there should be given to the mirrors rotary motions in opposite directions. The method of accomplishing this is clearly indicated in Fig. 3.

The hard steel points forming the contact with the specimen are set in the rings. The points themselves do not actually touch the specimen but rest in small holes drilled in a hard steel shoe, the inside of which had been cut to fit the diameter of the specimen, as shown at points *E* and *F* in Fig. 3. In order to keep the rings in contact with these points, springs were arranged as indicated. As the specimen swells, points *E* and *F* move apart from each other, causing the rings to slide and rotate the mirrors, each mirror registering the entire deformation. A positive contact between the rings

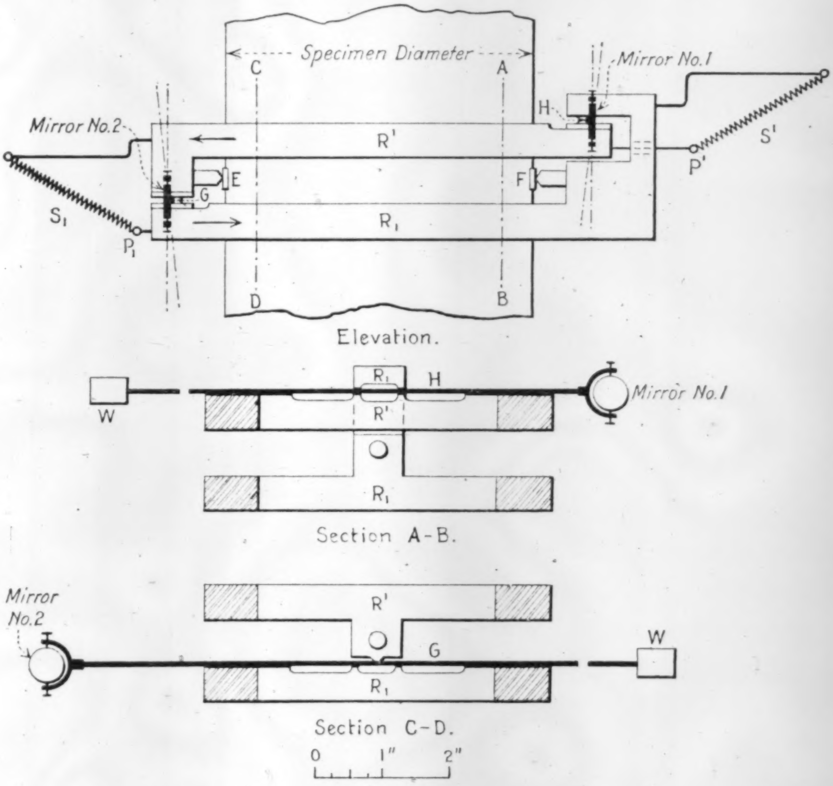
Specimen Diameter
C
A
Mirror No.1
Mirror No.2
H
R'
E
F
G
R₁
S₁
P₁
S'
P'
D
B
Elevation.
W
R₁
H
R'
Mirror No.1
R₁
Section A-B.
Mirror No.2
R'
W
G
R₁
Section C-D.
0
1"
2"

FIG. 3.—Diagram of Apparatus as Applied to Cylindrical Concrete Specimens for Direct Measurement of Poisson's Ratio.

and the rollers is secured in that the upper mirror, No. 1 in Fig. 3, bears at four points, two on each ring; whereas the roller for mirror No. 2 has but three points of contact, two on the lower ring and one on the upper. It is therefore necessary that the rollers throughout the distance of the bearing, about $\frac{3}{4}$ in., shall be of the same diameter. Drill steel rods 0.0784 in. in diameter were used for the rollers, and as nearly as could be determined by micrometer calipers the variation in diameter was less than 0.0001 in.

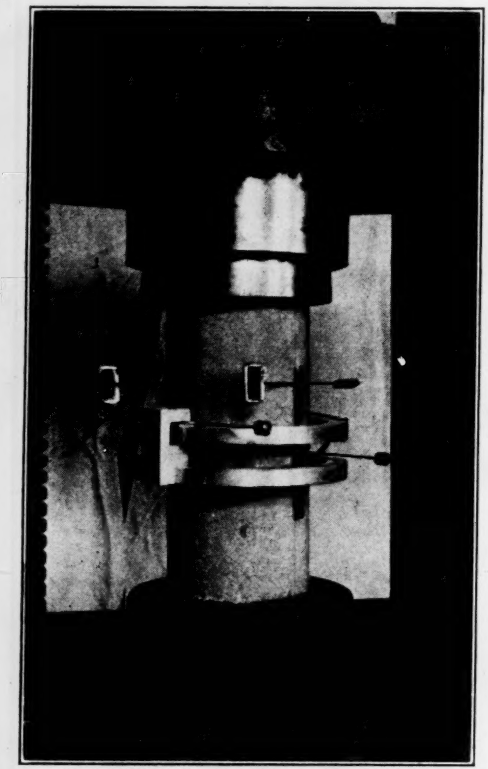

FIG. 4.—Apparatus for Determination of Poisson's Ratio Applied to Concrete Test Specimen Ready for Test.

To measure the deformation parallel to the line of action of the force (applied vertically) two mirrors are also mounted on the specimen diametrically opposite each other, as shown in Figs. 1 and 4. The vertical deformations were measured over a 4-in. gage length. It will be clear from Fig. 1 that the width W of the knife edge attached to the mirror to measure vertical deformations is the base line of the measurements. The actual widths of the knife edges used were for one mirror 0.2006 in. and for the other 0.1959 in. The distance D of the scales from each of the mirrors was so chosen that 1 in. on the scale indicated a deformation of the specimen of 0.001 in. over the 4-in. gage length. As it was entirely feasible to read the scale quite accurately to 0.01 in., vertical unit deformations of 2½ millionths of an inch (0.0000025 in.) per inch could be observed.

Referring to Fig. 3, it is seen that the diameter of the rollers carrying the mirrors which record the lateral or longitudinal deformation controls the sensitiveness of these measurements. If $r =$ the radius of the rollers, $d =$ the total lateral deformation, $D =$ the distance of the scale from the mirror and $S =$ the scale reading. we have the relation that

$$\frac{r}{d} = \frac{2D}{S}$$

The scales were placed at such a distance from the mirrors that a lateral deformation of two millionths of an inch (0.000002 in.) could be readily observed.

Two kinds of mirrors were used, glass sextant mirrors, which were cut in two, and polished stellite surfaces. Both were satisfactory. The mirrors for measuring the vertical deformation were glass sextant mirrors; those for observing the lateral deformations were polished stellite.

METHOD OF MAKING OBSERVATIONS

After the apparatus was in place, as shown in Fig. 4, four scales were placed at the proper distances from each mirror (two mirrors measuring the vertical deformations, the other two measuring the horizontal deformations). To read the scales, ordinary transit telescopes were used, and it was possible with little difficulty so to adjust the mirrors that the two scales for the vertical mirrors were observed in one telescope without moving it; and, likewise, the roller mirrors measuring the horizontal deformations had their scales so placed that they could be read with a single telescope.

Four observers were necessary; one at each telescope to read the scales, one to apply by hand the loads on the testing machine (a Riehlé 100,000-lb. two-screw type) and the fourth to set the counter weight of the testing machine to the required loading, and, also, to do the recording.

The loads were applied in increments of 100 lb. per sq. in. up to 1000 lb. per sq. in., and then at the rate of 200 lb. per sq. in. until failure of the specimen.

TABLE I.—DATA FOR DETERMINATION OF POISSON'S RATIO FOR CONCRETE CYLINDERS

Cylinders: Height, 9 in.; Diameter, 4.5 in.; Vertical Gage Length, 4 in.
Elastic Limit noted by horizontal lines. Poisson's Ratio = Horizontal Deformation ÷ Vertical Deformation.

Kind of Specimen	Mortar						Concrete						Mortar						Concrete						Concrete						Kind of Specimen
Laboratory No.	56		61		68		101		102		104		130		131		132		154		155		156		Core No. 1055		Core No. 1307		Core No 1648		Laboratory No.
Mix	1:2		1:2		1:2		1:2:3		1:2:3		1:2:3		1:2		1:2		1:2		1:2:4		1:2:4		1:2:4		1:2:4		1:2:4		1:2:4		Mix
Age, months	13		13		13		12		12		12		2		2		2		6		6		6		12		8 yr.		7 yr.		Age, months
	Deformations, 0.000001 in. per inch																														
Stress, lb. per sq. in.	Ver.	Hor.	Ver.	Hor.	Ver.	Hor.	Ver.	Hor.	Ver.	Hor.	Ver.	Hor.	Ver.	Hor.	Ver.	Hor.	Ver.	Hor.	Ver.	Hor.	Ver.	Hor.	Ver.	Hor.	Ver.	Hor.	Ver.	Hor.	Ver.	Hor.	Stress, lb. per sq. in.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	19	3	18	2	15	15	16	1	16	3	16	2	13	2	16	2	18	2	6	3	0	3	14	2	45	3	23	2	12	1	50
100	34	5	34	4	29	16	29	5	34	5	33	4	24	4	29	6	29	5	21	5	24	6	26	4	26	5	39	4	26	3	100
200	65	10	63	9	58	20	55	8	64	9	58	7	48	8	55	10	58	9	45	10	48	10	55	8	59	10	71	8	48	5	200
300	100	15	89	13	88	25	83	13	94	14	89	10	75	12	84	14	83	13	69	14	75	15	83	13	91	13	110	13	73	7	300
400	130	19	116	16	115	30	113	18	130	19	121	15	99	16	114	19	106	17	96	19	99	19	111	17	121	17	150	21	100	10	400
500	163	24	148	20	143	34	146	22	169	24	151	18	125	20	141	23	134	22	123	24	126	24	143	22	155	22	190	28	125	14	500
600	196	29	176	24	171	39	175	26	208	30	181	23	151	25	169	28	159	27	155	29	155	29	174	27	185	26	228	35	151	16	600
700	231	35	206	29	201	43	209	30	255	36	213	28	180	29	201	33	188	32	181	34	181	33	208	33	220	31	273	45	178	20	700
800	265	39	238	33	241	48	241	35	...	43	245	32	206	33	229	37	218	36	213	40	210	41	245	39	251	35	314	56	205	24	800
900	296	44	270	37	260	52	275	40	325	50	278	38	234	37	260	42	248	40	245	46	239	46	280	46	286	40	359	66	229	27	900
1000	329	49	300	42	291	58	309	45	370	57	311	42	263	41	291	47	274	45	271	52	269	53	315	52	318	44	401	79	255	32	1000
1200	398	58	363	51	350	69	389	55	463	77	383	55	318	50	354	58	333	52	343	68	335	65	394	68	385	56	489	109	303	39	1200
1400	468	68	428	61	416	79	459	66	563	100	455	72	375	59	416	68	398	63	418	82	406	81	486	89	454	69	580	140	349	48	1400
1600	543	80	493	71	481	90	538	77	669	132	540	87	444	71	481	78	455	72	504	101	475	96	589	120	525	83	683	184	395	59	1600
1800	614	91	564	81	550	102	626	92	794	177	649	118	513	83	549	90	524	81	596	126	561	117	723	162	600	97	785	239	441	71	1800
2000	681	100	638	93	616	116	729	111	950	258	794	195	573	95	623	102	593	92	706	165	663	140	850	254	689	123	894	313	488	85	2000
2200	766	113	713	105	708	181	875	163	...	443	946	326	669	113	714	115	658	100	844	227	763	198	1173	..	790	179	...	396	535	99	2200
2400	879	123	800	117	798	224	...	...	...	..	...	...	764	130	795	135	726	110	975	378	...	...	...	...	919	208	1154	520	585	118	2400
2600	989	140	905	134	916	253	...	...	...	...	...	...	888	154	...	...	830	126	...	...	...	...	...	...	1038	288	...	...	635	141	2600
Breaking Stress, lb. per sq. in	3400		4200		3400		2600		2500		2500		4400		3400		4900		2600		2900		2300		3500		3700		3900		Breaking Stress, lb. per sq. in
Poisson's Ratio, (within elastic limit)	0.142		0.138		0.155		0.160		0.141		0.130		0.143		0.166		0.164		0.180		0.170		0.157		0.136		0.108		0.120		Poisson's Ratio (within elastic limit)

One great advantage of this set-up is the fact that the apparatus can remain attached to the specimen up to the point of breaking without serious injury. As it was an easy matter, usually the mirrors were removed just before the specimen broke. Including the time necessary for setting up the apparatus, a complete test would occupy between one-half and three-quarters of an hour.

It will immediately occur to anyone that an essential condition to secure in the use of this apparatus is a temperature equilibrium between all parts of the apparatus, the specimen, and the air during the period of the tests. This can be readily ascertained, after the apparatus is set up, by observing the scales in the mirrors under no load and noting if any change occurs. If none is noted, it may be assumed that whatever change might be caused from this source is not sufficient to be recorded by the apparatus.

The tests which are here reported were made during the summer of 1923 in a laboratory in the basement of a building, the windows being closed and the curtains drawn in order that the illuminated scales would appear distinctly to the observer. Under these conditions, no variations due to temperature were observed. Much greater difficulty from temperature conditions would be experienced if steam heat were on at the time.

RESULTS OF OBSERVATIONS

The detailed results of the observations are shown in Table I. A few diagrams illustrative of the results are shown in Fig. 5 and need no explanation.

The limit of proportionality has been indicated in the tables by horizontal lines, and in general it will be noted that the limit of proportionality for vertical deformations, that is, parallel to the line of pressure, occurs approximately at the same load as that for the limit of proportionality for the horizontal deformations; the ratio of the horizontal deformations to the vertical deformations being Poisson's ratio.

The first three results are from tests made upon mortar cylinders, having a mixture of 1 part cement to 2 parts sand, 13 months old. The next three specimens are for gravel concrete, 1:2:3 mixture, 12 months old. The next three are for mortar cylinders, 1 part cement to 2 parts sand, 2 months old. The three following are for concrete cylinders, 1:2:4 mixture, 4 months old, while the last three were made up from cores taken from concrete roads, the concrete presumably being a 1:2:4 mixture. The first was a core from a road

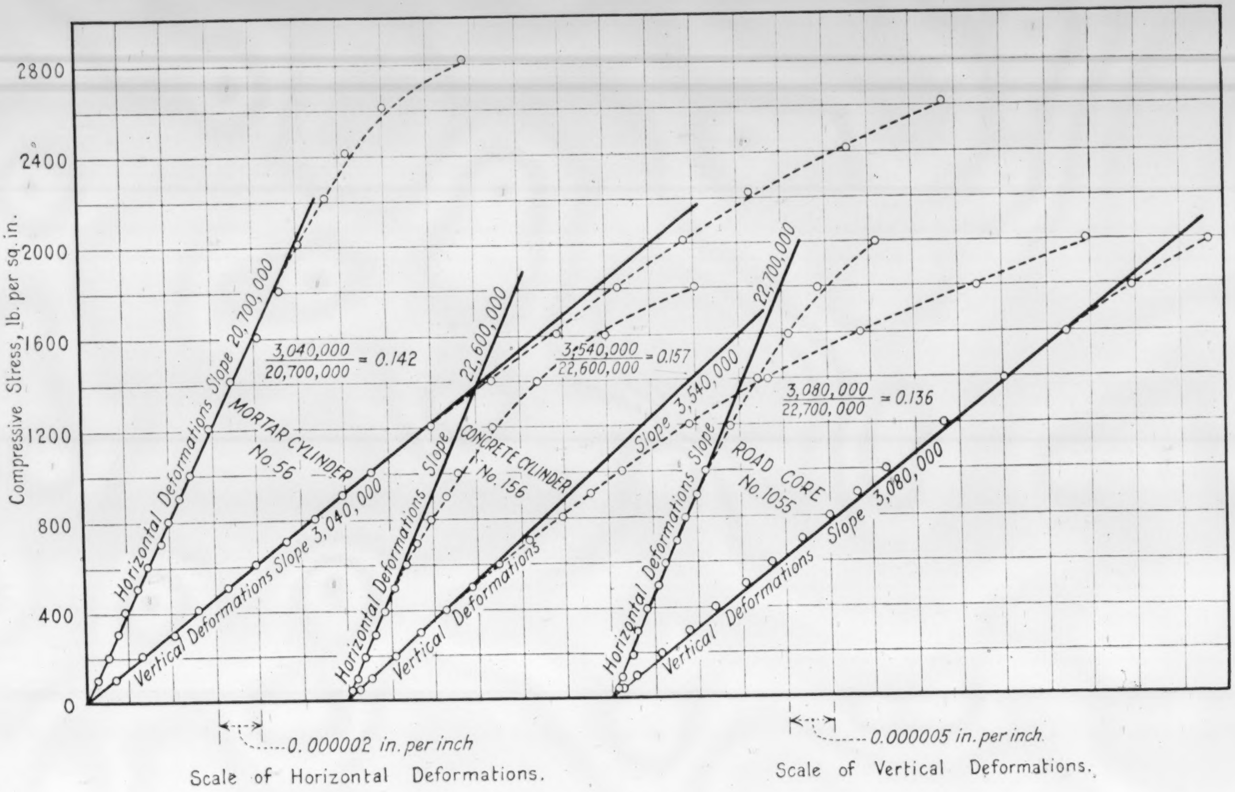

FIG. 5.—Typical Stress-Strain Curves Showing Vertical and Horizontal Deformations of Concrete under Vertical Pressure.

one year old; the second from a road eight years old; and the third from a road seven years old.

There is to be noted one feature that is consistent in all the tests made, and that is the straight-line relations of the vertical deformation and also of the corresponding horizontal deformations to the limit of proportionality, and that, therefore, for the loads less than these limits, the ratio of the horizontal deformation to the vertical deformation (Poisson's ratio) for a given specimen is a constant. The values of this ratio for a given set of specimens of the same age and mixtures are reasonably consistent.

For the 1:2 mortar cylinders 13 months old, the average value of Poisson's ratio is 0.145, while for the mortar cylinders of the same mixture 2 months old, the average value is 0.158.

The average for 1:2:3 concrete cylinders, 12 months old, is 0.144, and for the 1:2:4 mixtures, 6 months old, is 0.169. Also the values of the ratio obtained from the cores are less than for concrete not so old. These data would indicate that the age of the concrete may be a controlling factor. However, the number of specimens are too few to determine conclusively what may be the influence of variations in mixture and age upon the results

It will be noted that the lowest value found for a given specimen, that for a core taken from a road, is 0.108. The highest value recorded is 0.18 for a 1:2:4 laboratory specimen, 6 months old. The average value of Poisson's ratio for the fifteen specimens here reported is 0.147.

BIBLIOGRAPHY

A few references to reports of measurements of Poisson's ratio for concrete which will prove of particular interest in connection with this paper are given below:

Philosophical Magazine, London, Vol. VI, February, 1921, p. 206. Determination of values of Young's modulus and Poisson's ratio by the method of flexures by H. Carrington.

University of Wisconsin *Bulletin 466*, "Tests on Reinforced Concrete Columns," by M. O. Withey. On page 31 is described a device to measure lateral deformations on reinforced concrete.

He finds for stresses under one-fourth of the ultimate strength of concrete two months' old values for Poisson's ratio varying from 8 to 18 per cent.

Transactions, Am. Soc. of Civil Engrs., Vol. 78, 1915. C. G. Wentmore, *et al.* On page 105 is a description of apparatus for measuring lateral deformations of concrete columns.

University of Illinois *Bulletin 20*, by A. N. Talbot. Gives values of Poisson's ratio for concrete 60 days old between 0.10 and 0.16. Page 126.

Also see diagram on page 54. On page 16 is a brief description of apparatus used.

DISCUSSION

Mr. Walker. MR. STANTON WALKER[1] (*by letter*).—I have read Mr. Johnson's valuable paper with a great deal of interest. The simple apparatus which he has developed for measuring deformations in concrete in two directions simultaneously should encourage more extensive researches into the much discussed problem of the elastic properties of concrete.

The writer wishes to comment briefly on the statements in Mr. Johnson's paper concerning the shape of the stress-deformation curve for concrete. While, for our approximate methods of designing reinforced concrete, the exact shape of the stress-deformation curve may not be of great importance, we cannot refrain from expressing our belief that the initial curvature generally found in such stress-deformation curves is not entirely due to instrumental error. As stated in the closure of the discussion of our paper on Modulus of Elasticity of Concrete presented before the Society in 1919,[2] the behavior of our instrument (a five-point clamp-type compressometer), was carefully observed at early loads. The fact that some tests consistently show a curvature at early loads and others show nearly a straight line from the beginning seems sufficient evidence that the curvature was not due to instrumental error. The same instrument was used in determining the deformations of steel tubing under load and no evidence of curvature at the early loads was found. Parallel tests were made on the same concrete specimens, using the clamp-type instrument and a portable 6-in. Berry strain gage. The same results were obtained with both instruments. It is obvious that in the case of the Berry strain gage, conditions were identical for all loads.

It seems probable, however, that the shape of the curves shown in Mr. Johnson's Fig. 2 for the clamp-type instruments is largely due to instrumental errors. Most of them greatly exaggerate the typical curvature and the more erratic ones cannot be fitted accurately to the equation $s = Kd^n$ (where s is unit stress and d is unit deformation) which has been proposed by the writer and others as representing the stress-deformation relation for concrete.

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[1] Associate Engineer, Structural Materials Research Laboratory, Lewis Institute, Chicago.

[2] Stanton Walker, "Modulus of Elasticity of Concrete," *Proceedings*, Am. Soc. Testing Mats., Vol. XIX, Part II, p. 510 (1919); reprinted as *Bulletin No. 5*, Structural Materials Research Laboratory, Lewis Institute, Chicago.

Mr. Walker.

Curve *F* in Fig. 2 of Mr. Johnson's paper is said to represent data obtained from an instrument similar to the one used at our laboratory and described in our paper on "Modulus of Elasticity of Concrete." An equation of the form $s=Kd^n$ can be fitted to this curve only approximately. Such an approximation gives a value of about 0.53 for n, which is much lower than any values of this exponent found for our tests; 0.90 representing about the average for all of our data. The curves obtained by Mr. Johnson, using the clamp-type instruments, in most cases so obviously misrepresent the true stress-deformation relation, that we feel they should not be advanced as a valid argument that other data obtained by similar instruments are also in error.

The concrete tested by Mr. Johnson was of the nature which would be expected to give stress-deformation relations approximating a straight line. It would be interesting to see the results of tests made with this instrument on concrete of lower strengths and tested at earlier ages. We hope that the author will find the opportunity to extend his studies to a wider range of concrete, proportions, ages, conditions of curing, etc.; and we feel confident that if this is done, the characteristic stress-deformation relation for concrete, showing curvature from the origin, will be found.

EFFECT OF END CONDITION OF CYLINDER IN COMPRESSION TESTS OF CONCRETE

By H. F. Gonnerman[1]

Introduction

In making compression tests of concrete it has long been recognized by testing engineers that proper capping or bedding of the ends of the test cylinders is of prime importance. Experience and tests have shown that without a certain degree of care and uniformity in preparing the ends, the results will show considerable variation among themselves and may not be truly indicative of the strength of the concrete. The general adoption by testing laboratories of the methods of making and testing concrete specimens recommended in the Standard Methods of Making and Storing Specimens of Concrete in the Field (Serial Designation: C 31 – 21) and in the Tentative Methods of Making Compression Tests of Concrete (Serial Designation: C 39 – 21 T) of the American Society for Testing Materials has tended toward greater uniformity in test results. However, facilities are not always available nor conditions favorable for carrying out the recommendations in complete detail, and as there is an increasing demand for the testing of field concrete, it has seemed of sufficient importance to warrant the further investigation of methods of preparing cylinders for test which will insure reliable results without undue delay or expense.

The tests described in this paper were carried out primarily to determine the influence of uneven end surfaces and of different methods of capping on the reliability of compression tests of 6 by 12-in. concrete cylinders. Studies were also made of the effect of such factors as the deflection of the bed of the testing machine and the use of spherical bearing blocks in different positions.

About 3000 cylinders of four different mixes of concrete were used in the investigation.

These studies form a part of the experimental studies of concrete and concrete materials being carried out at the Structural Materials Research Laboratory through the cooperation of Lewis Institute and the Portland Cement Association.

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[1] Structural Materials Research Laboratory, Lewis Institute, Chicago, Ill.

OUTLINE OF TESTS

Two series of tests were carried out for the purpose of studying the influence of the following factors on the reliability of test results:

(*a*) Position of spherical bearing block;
(*b*) Deflection of table of testing machine;
(*c*) Material used for capping;
(*d*) Condition of capping;
(*e*) Molding with uneven base and cover plates;
(*f*) Inclination of axis, and top surface.

The first (Series 179) comprised compression tests of about 2100 6 by 12-in. concrete cylinders in which a range of mixes were selected that would include concrete of the quality ordinarily employed in construction work. The concrete mixes used (1:7, 1:5, 1:3½) were all of relative consistency 1.10 and the cylinders were generally tested at 28 days. For several of the methods studied, cylinders were also made for test at 7 days, 3 months, and 1 year. The specimens were made January to March, 1924.

The second series of tests (Series 179*A*) consisted of compression tests on about 900 cylinders. Most of the tests in this series were made to study the effect of unevenness in the top and bottom surfaces of the test cylinder on the load carried and on the uniformity of the results. The use of a Beaver Board sheet in overcoming the ill effects of poorly prepared ends was studied. Further studies of the position of the bearing block, deflection of the table of the testing machine and inclination of the axis and top surface of the cylinders were also made. Four concrete mixes, 1:7, 1:5, 1:3½ and 1:2, of relative consistency 1.10 were tested; for a few conditions tests were made on the 1:3½ mix using relative consistencies 0.90, 1.00, 1.25, 1.50 and 2.00. The cylinders were made in March and April, 1924, and were tested at 28 days.

CONCRETE MATERIALS AND PROPORTIONS

All concrete cylinders were made with portland cement consisting of a mixture of four brands purchased in Chicago. The same cement was used in both series; the neat cement used for capping was from the same lot. The results of chemical analysis, miscellaneous and physical tests of the cement are given in Table VIII.

The aggregate for concrete was sand and pebbles from Elgin, Ill., graded 0 to 1½ in. In order to reduce the variations in grading to a minimum the aggregate was screened into four sizes (0 to No. 4, No. 4 to ⅜ in., ⅜ to ¾ in., and ¾ to 1½ in.) and recombined to a predetermined sieve analysis. The fineness modulus of the mixed aggregate was 5.65.

The proportions of cement and aggregate reported in the tables are expressed as one volume of cement to a given number of volumes of dry rodded aggregate mixed as used. The quantities of each batch were determined by weight.

The concrete for most of the tests was mixed to a relative consistency of 1.10 which gave a flow of about 220 per cent when measured by means of the flow table using fifteen $\frac{1}{2}$-in. drops in 10 seconds.[1]

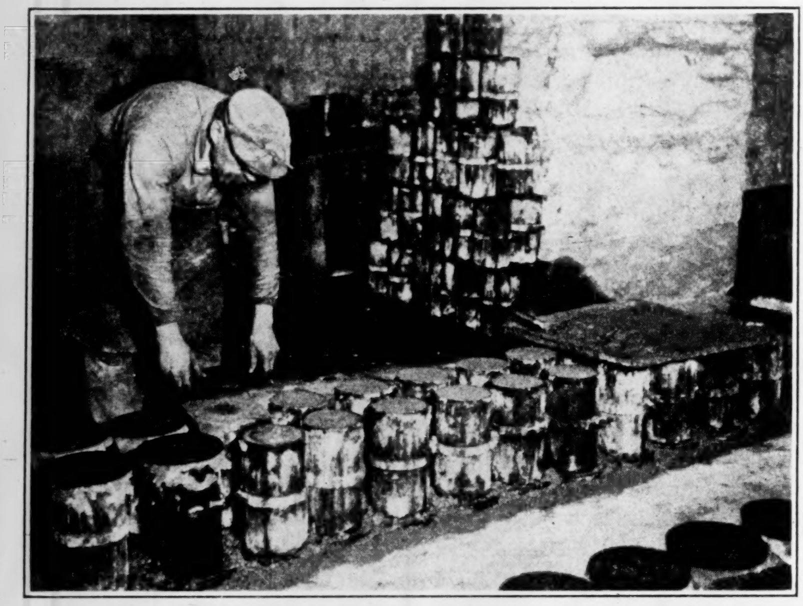

FIG. 1.—Standard Method of Capping Cylinders.

6 by 12-in. concrete cylinders molded on plane cast-iron base plates, capped with neat cement which stood from 2 to 6 hours before use and levelled with 8-in. plane cast-iron cover plates.

TEST PIECES

The concrete specimens used in comparing the various methods of testing were 6 by 12-in. cylinders. Ten cylinders made on different days were used for each condition of test. Each cylinder was made from a batch of about $\frac{1}{5}$ cu. ft. proportioned separately and mixed by hand with a blunted bricklayer's trowel in a shallow metal pan.

The concrete cylinder forms were of cold-drawn steel tubing slotted along one element. In making the cylinders, the forms were generally placed on cast-iron plates machined to a plane surface. In the studies of the effect of uneven and dished ends, the cylinders were molded on machined cast-iron or sheared steel plates or on pine boards as indicated in the tables. In studies of the effect of inclining the axis and the top surface of cylinder, the ends of the steel molds were cut to give the desired inclination.

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[1] The dimensions of the truncated cone-shaped metal form used for the flow test were: top diameter 6$\frac{3}{4}$ in., bottom diameter 10 in., height, 5 in.

The concrete was placed in the forms in 3 layers, each layer being rodded 30 times with a $\frac{5}{8}$-in. bullet-pointed steel rod. After molding, the specimens were capped as described below.

All concrete specimens were cured in a room the air of which was saturated with moisture and in which a uniform temperature of about 70° F. was maintained. Three days prior to test, the cylinders were removed from the moist room and cured in the air of the laboratory. Most of the tests were made at the age of 28 days. For a few conditions specimens were also made for test at 7 days, 3 months and 1 year. The 1-year tests have not been made.

Methods of Capping and Preparing Cylinders for Test.—The standard method of capping the cylinders was as follows: 2 to 6 hours after molding, a fairly stiff neat cement paste, which had been mixed previously and allowed to stand from 2 to 6 hours, was placed on the top of the cylinder. This paste was covered with a machined cast-iron plate about $\frac{1}{2}$ in. thick and 8 in. in diameter which was pressed down with a sliding and turning motion until it rested on the top of the cylinder form (see Fig. 1). By allowing the neat cement paste to stand for several hours before use, the tendency of the cap to shrink was largely overcome. Adhesion of the concrete to the capping plate and to the base plate was prevented by placing a sheet of paraffined tissue paper between the plate and the test specimen. If the capping paste became too stiff before use a small quantity of water was added and the paste remixed. It was generally not necessary to add water unless the paste stood for about 6 hours.

When specimens were capped with gypsum and with mixtures of portland cement and gypsum a small amount of the capping material was placed on a planed cast-iron table top and the trowelled top of the cylinder pressed down upon it to form a thin smooth cap. The table top was oiled to prevent the capping material from adhering when hardened. Care was taken to keep the cylinder in a vertical position during the capping operation in order to obtain parallel ends.

In a few tests the surfaces of the cylinder were capped in the testing machine with gypsum paste which was allowed to harden under load. The cylinder was placed in a bed of gypsum paste on the weighing table of the machine and the top of the cylinder covered with paste. The head of the testing machine with a spherical bearing block was then run down upon the cylinder until a load of about 750 lb. (25 lb. per sq. in.) was applied. The load was kept on the cylinder until the paste had hardened for 6 hours, when the test was completed. In the tests where a plane cast-iron base plate was used in molding the specimens, only the top surface of the cylinder was capped.

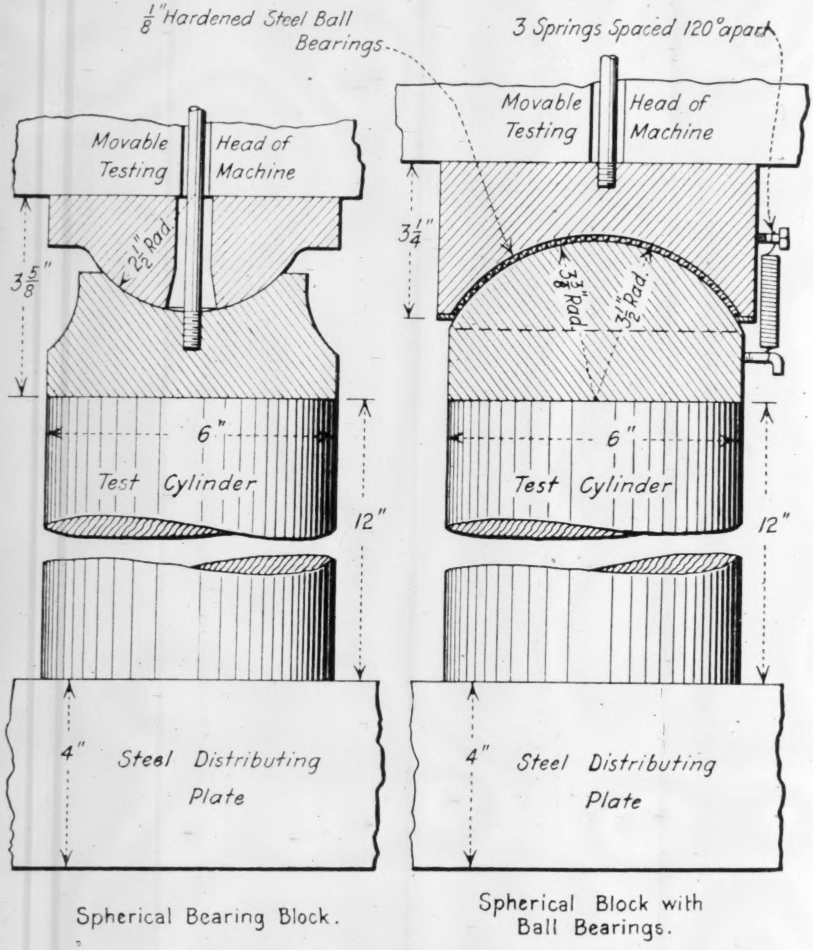
1/8" Hardened Steel Ball Bearings
3 Springs Spaced 120° apart
Movable Testing Head of Machine
Movable Testing Head of Machine
2 1/2" Rad.
3 5/8"
3 1/4"
3 3/8" Rad.
3 1/2" Rad.
6"
Test Cylinder
6"
Test Cylinder
12"
12"
4"
Steel Distributing Plate
4"
Steel Distributing Plate
Spherical Bearing Block.
Spherical Block with Ball Bearings.

FIG. 2.—Adjustable Bearing Blocks used in Tests.

Steel bearing blocks machined from drop forgings.

In some of the tests the cylinders were capped in a manner similar to that described for the standard method except that uneven and warped cover plates were used. In other tests the tops of the cylinders were trowelled to a smooth surface when molded and left to be capped at the time of test or to be tested using sheet materials as a substitute for capping.

For one set of specimens (Ref. 27, Table II) the tops were ground to a smooth plane surface in a surface grinder and were tested without additional capping.

The gypsum used for capping was No. 1 molding plaster manufactured by the U. S. Gypsum Co. Data of compression tests of the portland cement and gypsum mortar used for capping are given in Table VII.

SHEET MATERIALS AS SUBSTITUTES FOR CAPPING

Eight different kinds of sheet materials were used as substitutes for neat cement and gypsum capping to determine to what extent they would minimize the ill effects of poorly prepared ends. The sheet materials were cut into pieces about 7 in. square and were placed between the surface of the cylinder and the spherical block or the bottom bearing plate.

A brief description of each of the materials used follows:

Beaver Board.—A commercial wall board $\frac{3}{16}$ in. thick; manufactured by The Beaver Board Companies, Thorold, Ontario, Canada.

Blotting Paper.—A cotton blotting paper $\frac{1}{32}$ in. thick.

Cork Carpet.—No. 2 Armstrong Carpet $\frac{5}{16}$ in. thick; manufactured by the Armstrong Cork Carpet Co., Lancaster, Pa.

Lead.—Sheet lead $\frac{1}{16}$, $\frac{1}{8}$ and $\frac{1}{4}$ in. thick.

Leather.—Oak tan leather, 2-ply, $\frac{9}{32}$ in. thick.

Mill Board.—16-ply cardboard, $\frac{1}{16}$ in. thick.

Rubber.—Rubber sheeting, $\frac{1}{16}$, $\frac{1}{8}$, and $\frac{1}{4}$ in. thick.

White Pine Board.—$\frac{1}{8}$ in. thick, planed on both sides.

METHODS OF TESTING

All concrete specimens were tested in a 200,000-lb. Universal testing machine except those for Ref. 10 in Table I which were tested in a 300,000-lb. machine. Unless otherwise stated, a spherical bearing block was placed on top of the cylinder as indicated in Fig. 2. The bearing block was designed and made in the laboratory shops.[1]

In tests of Ref. 4 and 104, a bearing block, the spherical surfaces of which were separated by hardened steel balls (see Fig. 2) was used. In order to determine the influence of the position of the spherical bearing block on the test results, cylinders were tested for the following conditions:

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[1] For a description of the method used in machining the spherical bearing surfaces of this block, see *American Machinist*, p. 26, January 3, 1924.

Bearing block on top of cylinder;
Bearing block beneath cylinder;
Bearing blocks both on top and beneath cylinder;
Bearing block inverted on top of cylinder;
Bearing block off center $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$ and $\frac{1}{2}$ in.

One set of cylinders in each series was tested without a spherical bearing block.

Except as indicated in the tables, the cylinders were tested on a machined steel distributing plate 4 by 13 by 24 in. in size placed on the weighing table of the testing machine. The purpose of this plate was to eliminate possible ill effects resulting from the deflection of the weighing table of the testing machine, particularly at loads near the capacity of the machine.

DATA AND DISCUSSION

Standard of Comparison.—This investigation was undertaken to compare the reliability of the results obtained for several conditions of test. In order that variation in the concrete itself might not confuse the variations resulting from the different conditions used, it was important that the concrete be of uniform strength. In the preparation of the cylinders, the usual care was taken to obtain uniform materials and to make the cylinders in such a way that accidental errors of manipulation would be distributed throughout the series so that no one set of specimens would be unduly affected.

For convenience in reporting and studying the data, the basis of comparison for each series of tests was a group of specimens made and tested in accordance with the methods described in the Tentative Methods of Making Compression Tests of Concrete (Serial Designation: C 39 – 21 T) of the American Society for Testing Materials, which are the standard practices of this laboratory.

The cylinders for standard condition of test were:

1. Molded on plane, machined cast-iron base plates;
2. Capped when made;
3. Capped with neat cement which had been mixed and allowed to stand from 2 to 6 hours before use; a machined cast-iron cover plate was used to produce a cap having a plane surface;
4. Tested with spherical bearing block placed on top of specimen.

TABLE I.—INFLUENCE OF POSITION OF BEARING BLOCK AND DEFLECTION OF BED PLATE ON THE RESULTS OF COMPRESSION TESTS OF CONCRETE CYLINDERS—SERIES 179

Compression tests of 6 by 12-in. concrete cylinders.
Mix by volume.
Relative consistency 1.10 (Flow about 220).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to $1\frac{1}{2}$ in. (Fineness modulus, 5.65.)
Cement: a mixture of four brands purchased in Chicago.
Cylinders molded on 8-in. cast-iron base plates machined to a plane surface.
Cylinders capped 4 to 6 hours after making with neat cement (mixed 4 to 6 hours before use).
Cylinders cured in moist room until 3 days prior to test; remainder in air of laboratory.
Cylinders tested using a 6-in. spherical bearing block carefully centered on top and a 4 by 13 by 24-in. steel distributing plate below unless otherwise noted.
Strength-ratio is the ratio, expressed as a percentage, of the strength obtained for a given method of test to the average strength of Ref. 1 to 4.
Mean variation is the average arithmetical difference between the individual and average strengths for a given method of test expressed as a percentage of the average.
All tests made using a 200,000-lb. Universal testing machine except Ref. 10.
Each value is the average of 10 tests made on different days unless otherwise noted.

Reference	End Condition of Test Cylinder	1:7 Mix, 28 days			1:5 Mix									1:$3\frac{1}{2}$ Mix, 28 days		
					7 days			28 days			3 months					
		Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent
1	Standard condition	1140[a]	105	7.9	860[a]	101	6.6	2180[a]	101	6.7	3560	102	3.1	4680[a]	104	4.6
2	Spherical bearing block beneath cylinder	1050[b]	97	9.8	830[b]	98	7.1	2100[b]	98	5.0	3460	99	6.5	4310[b]	96	7.1
3	Spherical bearing block above and below cylinder	1080	100	5.6	870	102	7.9	2180	101	5.6	3440	98	5.3	4480	100	5.3
4	Ball-bearing spherical block on top of cylinder	1050[c]	97	6.4	840[c]	99	6.7	2090[c]	97	4.6	3540	101	3.1	4550[c]	101	8.4
	Average for all cylinders Ref. 1 to 4	1080[d]	100	8.1	850[d]	100	7.1	2150[d]	100	5.0	3500[d]	100	4.5	4500[d]	100	6.7
5	No spherical bearing block	880	81	10.0	780	92	9.7	1890	88	8.2	3120	89	8.9	3870	86	13.2
6	Spherical bearing block off center $\frac{1}{16}$ in.	...	...	...	...	...	...	2160	100	5.9	...	...	...	...	...	...
7	Spherical bearing block off center $\frac{1}{8}$ in.	...	...	...	...	...	...	2140	100	6.2	...	...	...	...	...	...
8	Spherical bearing block off center $\frac{1}{4}$ in.	...	...	...	...	...	...	2150	100	5.0	...	...	...	...	...	...
9	Standard condition, without lower distributing plate	1060	98	4.6	820	96	7.7	2100	98	5.7	3450	99	5.0	4540	101	4.7
10	Standard condition without lower distributing plate, 300,000-lb. machine	1100	102	4.5	930	109	5.9	2220	103	4.4	3650	104	3.8	4480	100	5.5
11	4 by 13-in. steel plate under cylinder on span of $23\frac{1}{2}$ in.	1090	101	8.2	880	103	7.5	2130	99	6.6	3560	102	4.1	4400	98	5.3
12	$2\frac{5}{8}$ by $8\frac{5}{16}$-in. steel plate under cylinder on span of $16\frac{5}{8}$ in.	1040	96	8.3	860	101	4.0	2160	100	5.0	3450	99	3.4	4330	96	6.9

[a] Average of 14 to 24 tests.
[b] Average of 15 to 18 tests.
[c] Average of 5 to 8 tests.
[d] Average of 49 to 58 tests.

In the first series it was originally planned to use the tests of the specimens for Ref. 1, Table I, as the standard of reference and to compare the results of other methods of test with this standard by means of strength-ratios, that is, the ratio (expressed as a percentage) of the average strength for a given method of test to the average strength for the standard method. However, a study of the data in Table I showed that several of the methods of test gave strength-ratios from 95 to 100 per cent and that the mean variations for these groups did not differ greatly from those shown for the standard group. Furthermore, the variation of the average of these groups from the standard was no greater than the variations within the standard group itself. From these considerations, it seemed desirable to include in the group of specimens forming the standard of reference those values in Table I which represented essentially the same conditions, and thus base the comparisons on a more representative number of specimens. Therefore in the study of the data in Tables I to IV, comparisons are based on the average of all tests for Ref. 1, 2, 3, and 4.

The method of test chosen as the standard is one which has been found to give reliable results. It permits of the failure of the specimen without restraint other than that induced by the friction between the end surfaces of the cylinder and the adjacent bearing plates which in this case is not important because of the length of specimen used. Such influences as splitting action due to the use of a yielding capping material, eccentricity of load, etc., are eliminated. This being true, it might be expected that an unfavorable method of test, besides showing a greater variation in the individual results from the average would also show a strength-ratio of less than 100 per cent. In the study of the data, therefore, the comparative value of the different methods of test is judged by the reduction in strength, as indicated by the strength-ratio, as well as by the uniformity of results as indicated by the mean variation. The mean variation is the average variation of the strengths of individual specimens from the average strength of the group. In the tables, the mean variation is expressed as a percentage of the average strength.

In the second series of tests (179*A*) comparisons are based on the group of specimens Ref. 101 (Table V) originally selected for this purpose. The tests for Ref. 103 and 104 show the same close agreement noted in Table I for similar conditions. The values for these two conditions might well have been included in the standard of comparison for this series, but their inclusion would not have affected the results since their strength-ratios and mean variations are essentially the same as Ref. 101.

Influence of Position of Bearing Blocks and Deflection of Bed Plates on Test Results.—In the foregoing discussion it was pointed out that the use of a spherical bearing block beneath the cylinder, both above and beneath the cylinder, and a bearing block the spherical surfaces of which were separated by hardened steel balls gave essentially the same results as when a spherical bearing block was placed on top of the cylinder, and that the standard of comparison was made to include the tests for these conditions. The equally close agreement in the similar tests in Table V was also pointed out.

The tests in which the spherical bearing block was not used (Ref. 5, Table I) show a reduction in strength of from 8 to 19 per cent and a higher mean variation, especially for the richer concrete. Data from similar tests for a 1:2 mix in Table V (Ref. 105) show a reduction in strength of 18 per cent and a mean variation about three times that for the standard condition. It follows from these results that the use of this method of test is not to be recommended.

The three groups of tests (Ref. 6, 7, and 8, Table I) in which the setting of the spherical bearing block was varied, show that for the 1:5 concrete tested, placing the bearing block off center as much as ¼ in. produced no noticeable effect on the strengths or on the reliability of the results. The strength-ratios for these three conditions in the first series were 100 per cent; the mean variations were about the same as the average for Ref. 1 to 4.

The tests in Series 179*A* (Ref. 106 and 107, Table V) for bearing block off center ⅛ in. and ¼ in. showed strength-ratios of only 93 and 92 per cent for the 1:5 mix and 99 and 97 per cent for the 1:3½ mix. Considering the limit of accuracy to be expected, this is a fair corroboration of the earlier tests. For the bearing block ½ in. off center (Ref. 108) the strength-ratios were 90 per cent for the 1:5 mix and 92 per cent for the 1:3½ mix. The values of mean variations for these tests were in general not materially different from those for the standard of comparison.

In the studies of the influence of deflection of bed plates, the deflection of the plates used to support the cylinder and of the table of the testing machine were measured for several of the tests. The measured deflections at loads of 30,000, 60,000 and 125,000 lb. which corresponded to the total loads at failure of cylinders from the three grades of concrete were as follows:

PLATE AND SPAN	MEASURED DEFLECTION IN INCHES CORRESPONDING TO LOAD AT FAILURE OF CYLINDER		
	1:7 MIX	1:5 MIX	1:3½ MIX
Table of testing machine in span of 32 in.	0.008	0.016	0.033
4 by 13-in. plate, 23½-in. span	0.005	0.010	0.021
2⅝ by $8\frac{5}{16}$-in. plate, 16⅝-in. span	0.007	0.014	0.030

TABLE II.—COMPRESSION TESTS OF CONCRETE CYLINDERS USING DIFFERENT METHODS OF CAPPING AND CAPPING MATERIALS—SERIES 179.

Compression tests of 6 by 12-in. concrete cylinders.
Age at test: 28 days.
Mix by volume.
Relative consistency 1.10 (Flow about 220).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to $1\frac{1}{2}$ in. (Fineness modulus, 5.65.)
Cement: a mixture of four brands purchased in Chicago.
Cylinders molded on 8-in. cast-iron base plates machined to a plane surface.
Tops of cylinders levelled off with trowel when made.
Cylinders cured in moist room until 3 days prior to test; remainder in air of laboratory.
Cylinders were tested using a 6-in. spherical bearing block carefully centered on top and a 4 by 13 by 24-in. steel distributing plate below.
All tests made on a 200,000-lb. Universal testing machine.
Strength-ratio is the ratio, expressed as a percentage, of the strength obtained for a given method of test to the average strength for Ref. 1 to 4 in Table I used as the standard of comparison.
Mean variation is the average of the arithmetical difference between the individual and average strengths for a given condition of test expressed as a percentage of the average.
Each value is the average of 10 tests made on different days unless otherwise noted.

Reference	End Condition of Test Cylinder	1:7 Mix			1:5 Mix			1: $3\frac{1}{2}$ Mix		
		Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent
1 to 4	Standard of Comparison	1080[a]	100	8.1	2150[a]	100	5.0	4500[a]	100	6.7
13	Top trowelled to smooth surface, no capping	1040	96	6.4	2020	94	5.9	3620	80	5.7
14	Capped with gypsum 15 min. before test	1050	97	5.7	2240	104	7.0	4530	101	6.7
15	Capped with gypsum 30 min. before test	1030	95	4.7	2120	99	7.1	4580	102	5.2
16	Capped with gypsum 1 hr. before test	1040	96	4.1	2180	101	5.1	4610	103	5.7
17	Capped with gypsum 3 hr. before test	1040	96	8.0	2050	95	5.8	4520	100	6.9
18	Capped with gypsum 6 hr. before test	1050	97	5.2	2170	101	6.0	4460	99	5.1
19	Capped with gypsum 24 hr. before test	1030	95	7.3	2170	101	5.1	4560	101	5.0
20	Capped with 1:1 mixture portland cement and gypsum 30 min. before test	1100	102	8.3	2230	104	3.5	4350	97	4.9
21	Capped with 1:1 mixture portland cement and gypsum 1 hr. before test	1100	102	6.2	2160	100	7.1	4390	98	7.3
22	Capped with 1:1 mixture portland cement and gypsum 3 hr. before test	1110	103	6.8	2160	100	5.7	4370	97	3.6
23	Capped with 1:1 mixture portland cement and gypsum 6 hr. before test	1080	100	5.7	2100	98	8.3	4530	100	4.7
24	Capped with 1:1 mixture portland cement and gypsum 24 hr. before test	1090	101	5.9	2190	102	4.4	4390	98	8.6
25	Capped with mixture of 1 part of gypsum to 3 parts portland cement 6 hr. before test	1100	102	7.4	2200	102	5.5	4470	99	6.3
26	Capped with mixture of 3 parts gypsum to 1 part portland cement 6 hr. before test	1090	101	6.4	2120	99	4.8	4580	102	3.4
27	Top ground to smooth surface on surface grinder	1080[b]	100	4.7	2280[b]	106	5.1	4630[b]	103	3.9
28	Capped with Beaver Board, $\frac{3}{16}$-in. thick	1060	98	3.8	2170	101	8.7	4090	91	3.8
29	Capped with white pine board, $\frac{1}{8}$-in. thick	990	92	7.3	2120	99	7.3	3920	87	6.5
30	Capped with millboard, $\frac{1}{16}$-in. thick	1090	101	5.7	1970	92	5.7	3780	81	7.7
31	Capped with leather, $\frac{9}{32}$-in. thick	1040	96	5.8	1960	91	6.6	3670	82	8.9
32	Capped with 3 thicknesses $\frac{1}{32}$-in. blotting paper	1000	92	6.3	2080	97	9.0	3470	77	6.2
33	Capped with sheet lead, $\frac{1}{16}$-in. thick	1030	95	9.9	1900	88	8.8	3330	74	8.5
34	Capped with sheet lead, $\frac{1}{8}$-in. thick	980	91	7.3	1940	90	5.8	3480	74	7.1
35	Capped with sheet lead, $\frac{3}{16}$-in. thick	960	89	6.5	1900	88	5.3	3460	77	5.3
36	Capped with cork carpet, $\frac{5}{16}$-in. thick	1010	93	8.1	1870	87	5.9	3140	70	6.5
37	Capped with sheet rubber, $\frac{1}{16}$-in. thick	880	81	9.9	1540	71	6.9	2100	47	7.2
38	Capped with sheet rubber, $\frac{1}{8}$-in. thick	960	89	7.9	1660	77	11.5	2920	65	12.4
39	Capped with sheet rubber, $\frac{1}{4}$-in. thick	1010	93	8.7	1710	80	9.5	2820	63	5.6

[a] Average of 49 to 58 tests.
[b] Average of 7 tests.

When expressed as a deflection in a length equal to the width of the cylinder the values for the richer mixture reduce to approximately 0.003 in. for the table of the testing machine; 0.005 in. for the 4-in. plate and 0.010 in. for the $2\frac{5}{8}$-in. plate and to about one-half these values for the 1:5 mix and to one-quarter for the 1:7 mix.

While the results for the tests bearing on the question of deflection of bed plates (Ref. 9, 11 and 12) are not entirely consistent, when strength-ratios are plotted in terms of amount of deflection, an indication of reduced strength with increased bending in the plate is found. In Series 179*A*, the tests without the distributing plate were repeated (Ref. 102) using a richer mix than in the previous tests. The data show no reduction in strength for this mix (1:2). It may be concluded, therefore, that the reliability of the tests of the cylinders placed directly on the table of the testing machine used is entirely satisfactory. However, the use of a distributing plate or block is recommended in tests of specimens of high strength or where a considerable deflection in the bed of the machine is known to exist.

The tests using the 300,000-lb. machine without the distributing plate beneath the cylinder (Ref. 10) show a very satisfactory mean variation, and an average strength-ratio slightly above normal.

Influence of Capping Materials and Methods of Capping.—Ref. 14 to 26, Table II show the results of using different materials for capping the top of the cylinder at the time of test. The bottoms of the cylinders for these tests were molded to a true plane and the tops trowelled off level with the form. The strength-ratios for these groups varied from 95 to 104 per cent and no systematic variation was apparent for the different conditions or mixes. These tests show that capping the top of the cylinder with any of the gypsum or mortar mixtures in the manner indicated, produced results substantially the same as the standard method in which the top of the cylinder was capped with neat cement at the time of making. That the tests are equal to the standard in reliability is also indicated by the uniformly low values of mean variation.

When the cylinders with the trowelled top were tested without capping (Ref. 13), the strength was reduced 4 to 6 per cent for the 1:7 and 1:5 mixes and about 20 per cent for the $1:3\frac{1}{2}$ mix, although there was no appreciable increase in the mean variation of the individual results. This method of test is not recommended even for the weaker concretes.

When the top of the cylinder was ground to a smooth surface (Ref. 27), no reduction in strength was found and the average value of the mean variation for the three mixes was very low. This method of preparing cylinders for test, while quite costly for the occasional individual test, might well prove economical where a large number of tests are to be made on specimens with irregular ends, such as cores drilled from pavements.

Sheet Materials as Substitutes for Capping.—Table II (Ref. 28 to 39) gives data of tests in which a variety of sheet materials were used between the top of the cylinder and the bearing block as a substitute for mortar capping. The top of the cylinder was trowelled to a smooth surface at the time of making and the bottom molded to a true plane by the use of a machined plate under the form. The strength-ratios and the average values of the mean variations for the three different mixes used in these tests are as follows:

Material	Thickness, in.	Strength-ratio of Average for Ref. 1 to 4, per cent			Mean Variation, per cent
		1:7 Mix	1:5 Mix	1:3½ Mix	
Beaver Board	$\frac{3}{16}$	98	101	91	5.4
White Pine	$\frac{1}{8}$	92	99	87	7.0
Mill Board	$\frac{1}{16}$	101	92	81	6.4
Leather	$\frac{9}{32}$	96	91	82	7.1
Blotting Paper (3 thicknesses used)	$\frac{1}{32}$	92	97	77	7.2
Sheet Lead	$\frac{1}{16}$	95	88	74	9.1
	$\frac{1}{8}$	91	90	74	6.7
	$\frac{3}{16}$	89	88	77	5.7
Cork Carpet	$\frac{5}{16}$	93	87	70	6.8
Rubber	$\frac{1}{16}$	81	71	47	8.0
	$\frac{1}{8}$	89	77	65	10.6
	$\frac{1}{4}$	93	80	63	7.9

It is significant that for all of the sheet materials used there was a decided falling off in strength-ratio with increase in the richness of the mix although the mean variations were generally no greater for the richer mixes. The fact that the rubber sheet gave the greatest difference in results between the lean and rich mixes, indicates that the cause of the lower strength was a splitting action induced by the tendency of the sheet material to flow laterally when under load.

These tests show that for the cylinders of 1:7 and 1:5 mix, with carefully trowelled tops and molded plane bases, a $\frac{3}{16}$-in. sheet of Beaver Board placed between the top of the cylinder and the spherical bearing block was a fairly good substitute for a cap of mortar or gypsum. For the 1:3½ mix, the results were not so satisfactory.

Cap Partly Removed.—In handling cylinders, it sometimes happens that part of the neat-cement capping is accidentally chipped off. The tests in Table III were made to determine how much of the capping might be removed without causing an appreciable reduction in strength. The data show that removing the cap for a distance of

$\frac{1}{4}$ to $\frac{1}{2}$ in. from the edge, that is, removing a circular segment of mid-ordinate $\frac{1}{4}$ to $\frac{1}{2}$ in. produces no material reduction in strength nor

TABLE III.—COMPRESSION TESTS OF CONCRETE CYLINDERS WITH PART OF CAP REMOVED—SERIES 179.

Compression tests of 6 by 12-in. concrete cylinders.
Age at test: 28 days.
Mix by volume.
Relative consistency 1.10 (Flow about 220).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to $1\frac{1}{2}$ in. (Fineness modulus, 5.65.)
Cement: a mixture of four brands purchased in Chicago.
Cylinders molded on 8-in. cast-iron base plates machined to a plane surface.
Cylinders capped 4 to 6 hours after making with neat cement (mixed 4 to 6 hours before use); part of cap removed with chisel after 48 hours as indicated.
Cylinders cured in moist room until 3 days prior to test; remainder in air of laboratory
Cylinders tested using a 6-in. spherical bearing block carefully centered on top and a 4 by 13 by 24-in. steel distributing plate below.
Strength-ratio is the ratio, expressed as a percentage, of the strength obtained for a given method to the average strength for Ref. 1 to 4 in Table I, used as the standard of comparison.
Mean variation is the average arithmetical difference between the individual and average strengths for a given method of test expressed as a percentage of the average.
All tests made using a 200,000-lb. Universal testing machine.
Each value is the average of 10 tests made on different days unless otherwise noted.

Reference	End Condition of Test Cylinder	1:7 Mix			1:5 Mix			$1:3\frac{1}{2}$ Mix		
		Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent
1 to 4	Standard of Comparison	1080[a]	100	8.1	2150[a]	100	5.0	4500[a]	100	6.7
40	Cap removed distance of $\frac{1}{4}$ in. from edge of cylinder	1130	105	6.8	2160	100	7.6	4540	101	2.3
41	Cap removed distance of $\frac{1}{2}$ in. from edge of cylinder	1090	101	5.9	2130	99	5.1	4330	96	3.9
42	Cap removed distance of 1 in. from edge of cylinder	1070	99	4.7	2020	94	6.9	4170	93	3.6
43	Cap removed distance of 2 in. from edge of cylinder	960	89	6.9	1660	77	11.7	2970	66	10.4
44	Cap removed distance of $\frac{1}{4}$ in. from edge of cylinder, replaced with 1:1 mixture of portland cement and gypsum 3 hours before test	1110	103	5.9	2150	100	8.1	4560	101	5.0
45	Cap removed distance of $\frac{1}{2}$ in. from edge of cylinder, replaced with 1:1 mixture of portland cement and gypsum 3 hours before test	1100	102	7.2	2140	100	3.8	4470	99	3.2
46	Cap removed distance of 1 in. from edge of cylinder, replaced with 1:1 mixture of portland cement and gypsum 3 hours before test	1060	98	3.7	2170	101	4.3	4310	96	6.9
47	Cap removed distance of 2 in. from edge of cylinder, replaced with 1:1 mixture of portland cement and gypsum 3 hours before test	990	92	6.1	2050	95	5.9	4100	91	7.9

[a] Average of 49 to 58 tests.

change in mean variation. This method of test may be considered to produce an effect somewhat similar to that resulting from the use of a spherical bearing block off center and the results confirm the conclusion drawn previously in regard to slight eccentricities of the bearing block.

Where the cap was removed for a distance of 1 in. there was a reduction in strength of about 7 per cent for the 1:5 and 1:3½ mixes; when 2 in. was removed, the reduction in strength ranged from 11 per cent for the 1:7 mix to 34 per cent for the 1:3½ mix.

TABLE IV.—COMPRESSION TESTS OF CONCRETE CYLINDERS FOR MISCELLANEOUS END CONDITIONS—SERIES 179.

Compression tests of 6 by 12-in. concrete cylinders.
Mix by volume.
Relative consistency 1.10 (Flow about 220).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in. (Fineness modulus, 5.65.)
Cement: a mixture of four brands purchased in Chicago.
Cylinders capped 4 to 6 hours after making with neat cement (mixed 4 to 6 hours before use).
Cylinders tested using a 6-in. spherical bearing block carefully centered on top and a 4 by 13 by 24-in. steel distributing plate below.
All tests made using a 200,000-lb. Universal testing machine.
Strength-ratio is the ratio, expressed as a percentage, of the strength obtained for a given method of test to the average strength for Ref. 1 to 4 in Table I, used as the standard of comparison.
Mean variation is the average arithmetical difference between the individual and average strengths for a given method of test expressed as a percentage of the average.
Each value is the average of 10 tests made on different days unless otherwise noted.

Reference	End Condition of Test Cylinder	1:5 Mix					
		28 days			3 months		
		Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent
1 to 4	Standard of Comparison	2150[a]	100	5.0	3500	100	4.5
48	Molded using cast-iron base and cover plates convex 0.003 in.	2190	102	5.5	3580	102	4.0
49	Molded using cast-iron base and cover plates convex 0.1 in.	1910	89	4.4	2840	81	5.2
50	Molded using cast-iron base and cover plates convex 0.2 in.	1650	77	6.9	2380	68	4.7
51	Molded using cast-iron base and cover plates concave 0.003 in.	2210	103	7.0	3620	103	4.9
52	Molded using cast-iron base and cover plates concave 0.1 in.	890	41	8.0	1190	34	6.3
53	Molded using cast-iron base and cover plates concave 0.2 in.	540	25	10.8	790	23	10.3
54	Axis of cylinder inclined ¼ in. in 12 in.; ends parallel	2160	100	5.2	....	....	....
55	Axis of cylinder inclined ½ in. in 12 in.; ends parallel	1980	92	12.9	....	....	....
56	Axis of cylinder vertical, top surface inclined ¼ in. in 6 in.	2200	102	3.3	....	....	....
57	Axis of cylinder vertical, top surface inclined ½ in. in 6 in.	2050	95	9.4	....	....	....
58	Standard, except cap was wet with water before test	2100	98	9.6	....	....	....
59	Standard, except cap was coated with cup grease before test	2100	98	4.9	....	....	....

[a] Average of 58 tests.

When the segment of the cap was replaced with mortar, somewhat better results were obtained for both the 1 and 2-in. segments, although for the latter condition there still remained a deficiency in strength of from 5 to 9 per cent.

Influence of Concave and Convex Ends.—Table IV gives results of tests of cylinders having concave and convex ends. The ends were formed by molding and capping in the usual way with plates machined to convex and concave surfaces having maximum deviations from a true plane of about 0.003, 0.1 and 0.2 in. The cylinders were tested as the other pre-capped specimens, that is, with no bedding of either mortar or sheet material. In Series 179*A* further tests were made to show the effect of using similar plates machined to give cylinders with bottoms convex 0.01, 0.02 and 0.05 in.

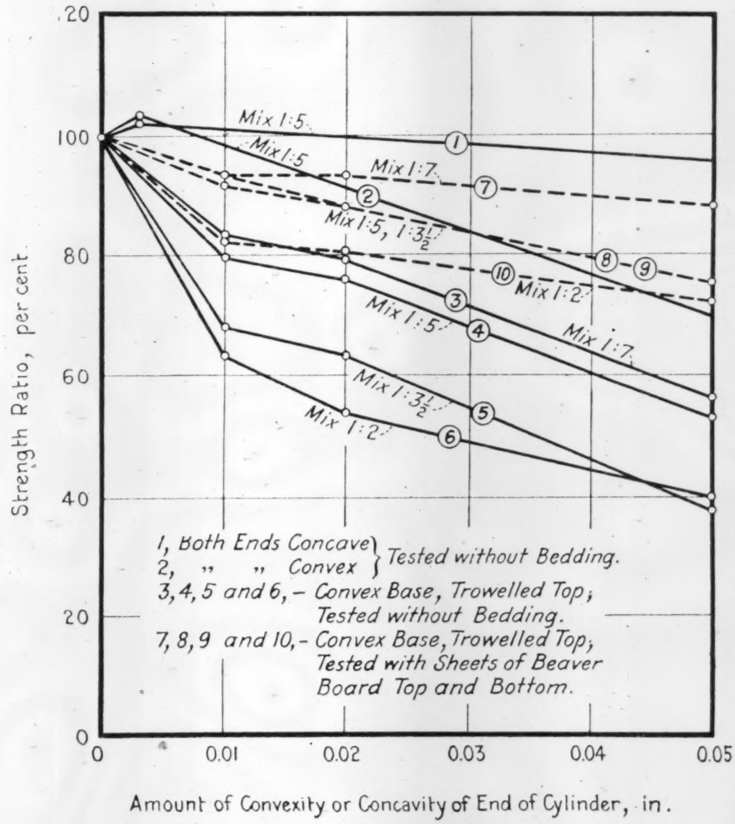

FIG. 3.—Effect of Convexity or Concavity of Cylinder Ends on the Reliability of Compression Tests.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Mix by volume.
Age at test, 28 days.
Each value is the average of 10 tests made on different days.
Data from Tables IV and V.

The tops were trowelled smooth. Some of the cylinders were tested as made, without bedding; others were tested with sheets of Beaver Board at both top and bottom; one set was tested using gypsum-mortar bedding both top and bottom. Other cylinders were made in

TABLE V.—COMPRESSION TESTS OF CONCRETE CYLINDERS FOR DIFFERENT END CONDITIONS—SERIES 179*A*.

Compression tests of 6 by 12-in. concrete cylinders.
Age at test: 28 days.
Mix by volume.
Relative consistency 1.10 (Flow about 220).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in. (Fineness modulus, 5.65).
Cement: a mixture of four brands purchased in Chicago.
Cylinders molded on 8-in. cast-iron base plates machined to a plane surface unless otherwise noted.
Cylinders capped 4 to 6 hours after making with neat cement (mixed 4 to 6 hours before use) unless otherwise noted.
Cylinders cured in moist room until 3 days prior to test; remainder in air of laboratory.
Cylinders tested using a 6-in. spherical bearing block carefully centered on top and a 4 by 13 by 24-in. steel distributing plate below, except Ref. 105.
Strength-ratio is the ratio, expressed as a percentage, of the strength obtained for a given method of test to the strength of similar concrete when tested in accordance with the "Standard Condition."
Mean variation is the average arithmetical difference between the individual and average strengths for a given method of test expressed as a percentage of the average.
All tests made using a 200,000-lb. Universal testing machine.
Each value is the average of 10 tests made on different days.

Reference	End Condition of Test Cylinder	1:7 Mix			1:5 Mix			1:3½ Mix			1:2 Mix		
		Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent
	CYLINDERS CAPPED WITH NEAT CEMENT WHEN MADE												
101	Standard condition...	1190	100	3.9	3010	100	4.1	4690	100	4.7	5750	100	3.8
102	Standard; without lower distributing plate............	....	...	...	....	...	...	....	...	...	5660	99	4.7
103	Bearing block inverted on top of specimen............	....	...	...	....	...	...	....	...	...	5770	100	4.5
104	Ball bearing block...	....	...	...	....	...	...	....	...	...	5680	99	3.7
105	No bearing block....	....	...	...	....	...	...	....	...	...	4720	82	12.1
106	Bearing block off center $\frac{1}{8}$ in..........	....	...	...	2810	93	8.9	4630	99	5.1	....	...	...
107	Bearing block off center $\frac{1}{4}$ in..........	....	...	...	2780	92	7.1	4530	97	4.4	....	...	...
108	Bearing block off center $\frac{1}{2}$ in..........	....	...	...	2700	90	6.3	4310	92	3.8	....	...	...
109	Axis of cylinder inclined $\frac{1}{4}$ in. in 12 in.; ends parallel...	....	...	...	....	...	...	4540	97	6.1	....	...	...
110	Axis of cylinder inclined $\frac{1}{2}$ in. in 12 in.; ends parallel...	....	...	...	....	...	...	4430	95	4.2	....	...	...
111	Sides of cylinder vertical; top surface inclined $\frac{1}{4}$ in. in 6 in...............	....	...	...	....	...	...	4580	98	6.1	....	...	...
112	Sides of cylinder vertical; top surface inclined $\frac{1}{2}$ in. in 6 in...............	....	...	...	....	...	...	4480	96	5.2	....	...	...
	CYLINDERS CAPPED WITH GYPSUM IN TESTING MACHINE UNDER LOAD OF 25 LB. PER SQ. IN. FOR 6 HR. BEFORE TEST												
113	Molded on plane cast-iron base plates; top trowelled smooth...........	....	...	...	....	...	...	4630	99	3.9	....	...	...
114	Molded on cast-iron base plates concave 0.05 in.; top trowelled smooth......	....	...	...	....	...	...	4200	90	4.6	....	...	...

TABLE V—*Continued*

Reference	End Condition of Test Cylinder	1:7 Mix			1:5 Mix			1:3½ Mix			1:2 Mix		
		Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent
	CYLINDERS TESTED AS MADE WITHOUT ADDITIONAL CAPPING OR SHEETS												
115	Cylinder molded using ¼-in. plane sheared steel plates top and bottom....	1060	89	5.7	2750	91	6.3	4390	94	3.6	5640	98	4.8
116	Cylinder molded using ¼-in. warped sheared steel plates top and bottom....	950	80	8.7	2300	76	8.3	3580	76	11.8	3900	68	9.2
117	Cylinder molded on cast-iron base plate concave 0.01 in.; top trowelled smooth..........	990	83	6.6	2390	79	6.7	3210	68	8.6	3630	63	9.0
118	Cylinder molded on cast-iron base plate concave 0.02 in.; top trowelled smooth..........	940	79	8.9	2290	76	4.5	2960	63	7.6	3130	54	6.5
119	Cylinder molded on cast-iron base plate concave 0.05 in.; top trowelled smooth..........	670	56	6.3	1590	53	6.5	1760	38	10.7	2280	40	10.6
120	Cylinder molded on 1-in. pine board; top trowelled smooth...	980	82	8.8	2440	81	8.8	3190	68	3.7	3860	67	9.1
	CYLINDERS TESTED WITH BEAVER BOARD SHEETS TOP AND BOTTOM												
121	Cylinder molded using ¼-in. plane sheared steel plates top and bottom....	1140	96	5.2	2750	91	6.4	4650	99	5.6	5520	96	3.2
122	Cylinder molded using ¼-in. warped sheared steel plates top and bottom....	1100	92	6.5	2680	89	7.4	4380	94	4.3	5350	93	4.3
123	Cylinder molded on cast-iron base plate concave 0.01 in.; top trowelled smooth..........	1110	93	5.7	2770	92	6.6	4350	93	2.8	4690	82	4.0
124	Cylinder molded on cast-iron base plate concave 0.02 in.; top trowelled smooth..........	1110	93	7.1	2650	88	7.0	4110	88	5.0	4590	80	5.5
125	Cylinder molded on cast-iron base plate concave 0.05 in.; top trowelled smooth..........	1050	88	8.5	2250	75	9.0	3500	75	4.2	4130	72	4.3
126	Cylinder molded on 1-in. pine board; top trowelled smooth...	1160	98	4.3	2790	93	4.7	3990	85	7.5	4550	79	5.3

which the standard method of molding and capping was followed except that $\frac{1}{4}$-in. sheared steel plates were used for the base and cover plates. Field specimens are sometimes made using such plates, and as earlier tests showed that small irregularities affected the results very materially, the tests using sheared plates were included. Sheared plates were selected some of which were approximately true planes, and others which were dished or warped about 0.01 in. Cylinders were tested both without bedding and using Beaver Board sheets both top and bottom. Table V gives the results of the tests for Series 179*A*.

Fig. 3 shows data from both series plotted with strength-ratios as ordinates and amount of convexity or concavity as abscissas. Curves 1 and 2, which give results of tests on 1:5 concrete from Table IV, were transferred from a drawing of smaller scale as only one value fell within the range of abscissas covered by the figure. Except for the values corresponding to 0.003 in. convexity, which are about normal, these curves show that convex ends reduce the cylinder strength about four times as much as ends which are concave a similar amount.

The results of tests on cylinders with convex ends for different mixes and methods of test are shown in Table V (Ref. 117, 118, 119, 123, 124 and 125). These data can be more easily compared by the curves of Fig. 3. Curves 3, 4, 5, and 6 show the results for cylinders of 1:7, 1:5, 1:3½ and 1:2 concrete having molded convex bases and trowelled tops, tested without bedding of either mortar or sheet material. Curves 7, 8, 9 and 10 show the results for similar specimens tested with sheets of Beaver Board both top and bottom.

It will be noted that the cylinder strength is reduced in all cases with an increase in the amount of convexity and with the richness of the mix; also that the specimens tested using the Beaver Board sheets show a loss of strength about half as much as those tested without bedding.

The cylinders for Ref. 114 were of 1:3½ mix and had bases convex 0.05 in. and trowelled tops. They were tested with gypsum bedding top and bottom. When compared with similar specimens tested without bedding and with Beaver Board sheets (Ref. 119 and 125) the strength-ratios are as follows:

KIND OF BEDDING	STRENGTH-RATIO, PER CENT
None	38
Beaver Board sheets top and bottom	75
Gypsum top and bottom	90

These strength-ratios show that while the gypsum bedding helped materially it did not entirely overcome the effect of the convex end. It should be noted that these comparisons are for rather rich concrete; for ordinary mixes the effect of the bedding in overcoming convexity would probably have been greater.

The significant feature of these tests of cylinders with convex ends is the marked effect of very small irregularities. It was because of the importance of this feature of the tests that the tests with the sheared steel plates (Ref. 115, 116, 121 and 122) were undertaken, as such plates are sometimes used. The sheared plates were from warehouse stock and were 8 in. square. They were carefully measured and those which showed a deviation of less than 0.004 in. from a true plane were classed as plane plates; those which were about 0.01 in. out of true were classed as warped plates. In molding the cylinders, the warped plates were used to give convex ends both top and bottom.

TABLE VI.—COMPRESSION TESTS OF CONCRETE OF DIFFERENT CONSISTENCIES FOR DIFFERENT END CONDITIONS OF TEST CYLINDER—SERIES 179*A*.

Compression tests of 6 by 12-in. concrete cylinders.

Mix 1: $3\frac{1}{2}$ by volume.

Aggregates: sand and pebbles from Elgin, Ill., graded 0 to $1\frac{1}{2}$ in. (Fineness modulus, 5.65.)

Cement: a mixture of four brands purchased in Chicago.

Age at test: 28 days.

Cylinders capped 4 to 6 hours after mixing with neat cement (mixed 4 to 6 hours before use).

Cylinders cured in moist room until 3 days prior to test; remainder in air of laboratory.

Cylinders tested using a 6-in. spherical bearing block carefully centered on top and a 4 by 13 by 24-in. steel distributing plate below.

All tests made using a 200,000-lb. Universal testing machine.

Strength-ratio is the ratio, expressed as a percentage, of the strength obtained for a given method of test to the strength obtained from similar concrete tested in accordance with the standard condition.

Mean variation is the average arithmetical difference between the individual and average strengths for a given method of test expressed as a percentage of the average.

Strengths are given in pounds per square inch.

Each value is the average of 10 tests made on different days.

Reference	End Condition of Test Cylinder		Relative Consistency of Concrete					
			0.90 (.60)[a]	1.00 (.66)	1.10 (.73)	1.25 (.82)	1.50 (.99)	2.00 (1.32)
101	Standard condition	Compressive Strength, lb. per sq. in.	5480	5370	4690	3750	2420	1150
		Strength-Ratio, per cent	100	100	100	100	100	100
		Mean Variation, per cent	5.5	4.7	4.7	8.7	4.8	6.2
127	Molded using $\frac{1}{4}$-in. warped, sheared steel plates top and bottom; tested without Beaver Board sheets.	Compressive Strength, lb. per sq. in.	4210	3550	3580	2850	2040	1000
		Strength-Ratio, per cent	77	66	76	76	84	87
		Mean Variation, per cent	11.1	10.0	11.8	8.9	9.1	13.3
128	Molded using $\frac{1}{4}$-in. warped, sheared steel plates top and bottom; tested with Beaver Board sheets top and bottom	Compressive Strength, lb. per sq. in.	5210	4850	4380	3590	2180	1190
		Strength-Ratio, per cent	95	90	94	96	90	103
		Mean Variation, per cent	3.2	4.5	4.3	3.7	6.1	8.1

[a] Water-cement ratio.

The data in Table V show that for the cylinders tested without bedding, those made using the sheared plates which were approximately plane showed a reduction in strength averaging 7 per cent; for the warped plates the reduction in strength ranged from 20 per cent for the 1:7 mix to 32 per cent for the 1:2 mix. When tested with Beaver Board sheets both top and bottom the reductions in strength for the two conditions were about one-half to one-third as great as when tested without the sheets. These results are not plotted in Fig. 3 but they agree fairly well with the strength-ratios shown by the curves when the amount of convexity is taken into account.

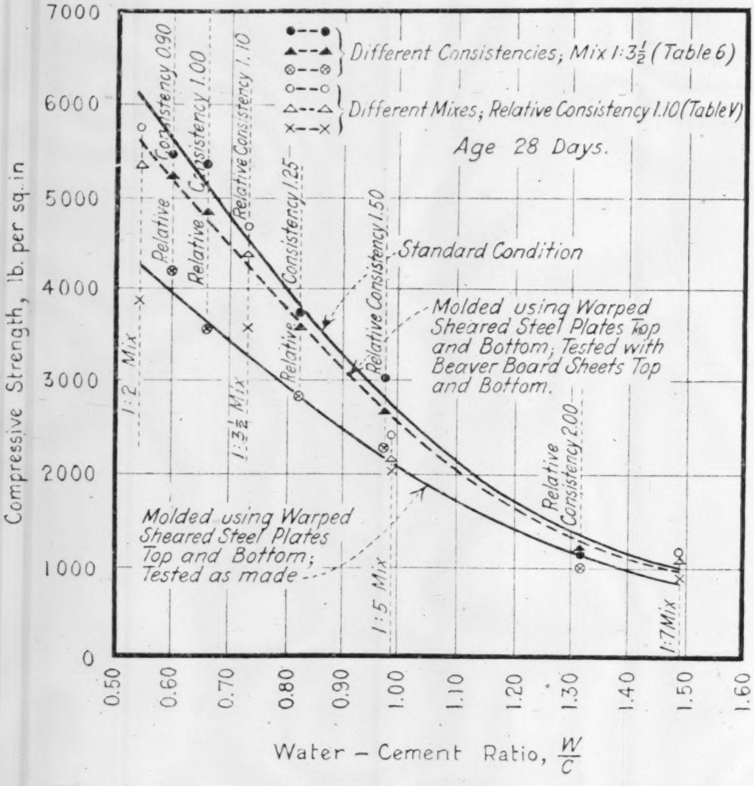

FIG. 4.—Water-Ratio-Strength Relation as Influenced by Condition of Cylinder Ends.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Mix by volume.
Each value is the average of 10 tests made on different days.
Data from Tables V and VI.

Table VI (Ref. 127 and 128) gives data of further tests of cylinders molded with warped sheared steel plates top and bottom in such a way as to give convex ends. Parallel tests on cylinders of 1:3½ mix for six different consistencies were carried out. Some of the cylinders were tested without bedding and some with Beaver Board sheets top and bottom. The data from these tests are shown in Fig. 4 where compressive strengths are plotted against water-cement ratios. For purpose of comparison a curve based on tests of cylinders molded and tested in the standard way is included. The curves show a reduction in strength of from 2 to 9 per cent for the cylinders tested with Beaver Board and a reduction of from 17 to 30 per cent for those tested without bedding. The curves show quite clearly that the reduction in strength due to the convex ends is greater for the stronger concretes.

TABLE VII.—COMPRESSION TESTS OF MORTAR USED FOR CAPPING—SERIES 179.

Compression tests of 2 by 4-in. cylinders.

The mortar was mixed to the consistency ordinarily used in capping concrete cylinders and building units in laboratory.

The portland cement mortar which stood 6 to 8 hours required additional mixing water before molding cylinders in order to bring it to the same plasticity used for capping.

Each value is the average of 5 tests made on different days.

Capping Material		Mixing Water, per cent by weight of dry materials	Time Mixed Before Molding hours	Curing Condition	Compressive Strength, lb. per sq. in.									
Cement, per cent by weight	Gypsum, per cent by weight				15 minutes	30 minutes	1 hour	3 hours	6 hours	1 day	2 days	3 days	7 days	28 days
0	100	50	0	Air..........	520	1040	1200	1180	1280	1280	1300	1180	1440	2650
25	75	50	0	Air..........	...	1070	1020	1030	950	1030	1000	1040	1300	2300
50	50	50	0	Air..........	...	540	550	470	470	600	790	900	1180	2160
75	25	40	0	Air..........	...	180	190	180	210	640	890	1170	1720	3010
100	0	33	0	Air..........	...	....	....	....	....	1570	2610	3560	4710	4730
100	0	33	0	Moist Room	...	....	....	....	....	1740	2640	3360	5000	8240
100	0	33	2	Air..........	...	....	....	....	....	1560	2610	3610	4930	4520
100	0	33	2	Moist Room	...	....	....	....	....	1540	2490	3270	4900	8100
100	0	33	4	Air..........	...	....	....	....	....	1490	2790	3690	5000	4690
100	0	33	4	Moist Room	...	....	....	....	....	1560	2540	3530	5340	8650
100	0	34	6	Air..........	...	....	....	....	....	1170	2270	3160	4690	4540
100	0	34	6	Moist Room	...	....	....	....	....	1140	2100	2930	4870	8260
100	0	35	8	Air..........	...	....	....	....	....	860	1880	2770	4210	4120
100	0	35	8	Moist Room	...	....	....	....	....	840	1780	2480	4080	6710

In plotting Fig. 4, the data from cylinders of other mixes, made and tested under similar conditions were included in order to obtain a wider range for the water-ratio-strength curves. These curves are similar in form to those given in other publications of this laboratory, and show the important relation of the water-cement ratio to the compressive strength of the concrete.

It is apparent from these data that in tests of concrete care must be taken to secure cylinder ends that are true planes. This is the most important feature of this investigation. The loss of strength due to a small convexity of the cylinder end is very much greater than that due to inclinations of the axis or top surface of the cylinder as will be shown later.

Use of Pine Board Bases for Molding Cylinders.—Field specimens are frequently molded by placing the forms directly on a smooth board. Tests were made to approximate this condition. The molds were placed on a 1-in. pine board during the molding operation and the tops of the cylinders were trowelled smooth.

The cylinders (Ref. 120 and 126, Table V) showed strength-ratios from 82 per cent for the 1:7 mix to 67 per cent for the 1:2 mix when tested without capping of any kind. When tested with sheets of Beaver Board both top and bottom the corresponding strength-ratios ranged from 98 to 79 per cent. The deviation of the cylinder bases from a true plane varied from a few thousandths to about one-tenth of an inch. As this represents what might be expected in cylinders similarly made in the field, the low strengths obtained are significant. The results are comparable to those obtained for cylinders with convex ends (see Fig. 3).

Table VIII.—Tests of Cement—Series 179 and 179*A*.

Chemical Analysis of Cement

Tests made in accordance with the Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.
Values are the average of 2 tests expressed as percentages by weight.

Cement	Silica, SiO_2	Iron Oxide, Fe_2O_3	Aluminum Oxide, Al_2O_3	Calcium Oxide, CaO	Magnesium Oxide, MgO	Sulfuric Anhydride, SO_3	Loss on Ignition	Insoluble Residue
7153......	22.42	3.32	5.85	62.10	2.71	1.82	1.15	0.18

Miscellaneous Tests

Tests made in accordance with the Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.
Each value is the average of 2 determinations.

Cement	Fineness Residue on No. 200 Sieve, per cent	Water for Normal Consistency, per cent by weight	Time of Setting				Soundness Test (over boiling water)
			Vicat Needle		Gillmore Needle		
			Initial	Final	Initial	Final	
7153......	18.4	23.5	3 hr. 40 min.	6 hr. 50 min.	5 hr. 25 min	7 hr. 55 min.	O.K.

Mortar-Strength Tests

1:3 standard sand mortar.
Tension tests of briquettes and compression tests of 2 by 4-in. cylinders.
Specimens cured in water; tested damp.
Each value is the average of 5 specimens made on different days.

Cement	Mixing Water, per cent	Tensile Strength of Briquettes, lb. per sq. in.				Compressive Strength of 2 by 4-in. Cylinders, lb. per sq. in.			
		7 days	28 days	3 months	1 year[a]	7 days	28 days	3 months	1 year[a]
7153......	10.4	310	405	450	....	1820	2930	3950	....

[a] 1-year tests not due.

Influence of Inclined Axis and Inclined Ends.—Tables IV and V (Ref. 54, 55, 109 and 110) give results of tests in which the ends of the cylinders were parallel but the axis of the cylinder was inclined $\frac{1}{4}$ and $\frac{1}{2}$ in. from the vertical in a length of 12 in. The tests show that for parallel ends an inclination of the cylinder axis of $\frac{1}{4}$ in. caused no appreciable reduction in strength; an inclination of $\frac{1}{2}$ in. caused a reduction of from 5 to 8 per cent.

Data on tests of cylinders having their axes at right angles to the base but the top surface inclined $\frac{1}{4}$ and $\frac{1}{2}$ in. in a distance of 6 in. are given in Tables IV and V (Ref. 56, 57, 111 and 112). These results show no reduction in strength where the top was inclined $\frac{1}{4}$ in. from the horizontal and about 5 per cent reduction for an inclination of $\frac{1}{2}$ in. These tests show how relatively unimportant are minor inclinations of the ends or axis in comparison with small convexities in the end surfaces.

Tests of Cylinders with Ends Greased or Wetted.—Wetting and greasing the cylinder top before testing (Ref. 58 and 59, Table IV), while showing very slight reductions in strength cannot be regarded as particularly significant, as the 2 per cent reduction found might easily be accounted for by the accidental variations occurring in any two sets of cylinders.

Uniformity of Results.—One of the interesting features of this investigation was the rather surprising uniformity exhibited by the cylinders tested by any of the methods tried. It was expected that the study of the mean variation would give considerable information on the relative value of the different methods of test. This expectation, however, was not fully realized. Except for a few of the methods used, the mean variation of the individual strengths from the average strength did not differ greatly from that shown by the group of cylinders used for the standards.

The greatest variation in individual results was found in the tests without adjustable bearing block (Ref. 5 and 105) for which the average mean variation for the 28-day tests of the four grades of concrete was 10.9 per cent; the highest value was 13.2 per cent for the 1:3$\frac{1}{2}$ mix. For the tests with $\frac{1}{8}$-in. sheet rubber, high mean variations were also found. The values ranged from 7.9 to 12.4 per cent and averaged 10.6 per cent. The lowest mean variations were found for the standard tests in Series 179*A* and for the cylinders with tops ground to a smooth surface; the values were 4.1 and 4.5 per cent, respectively. It appears that the reliability of a given method of test should not be judged solely by the mean variation of the individual test results from the average. The mean variation may be low but it does not necessarily follow that the strength obtained represents the true strength of the material tested.

Bibliography.—The accompanying bibliography gives references to other tests bearing on this subject. The brief notes which are given for several of the references reflect the views expressed therein and do not indicate the opinion of the author of this paper.

CONCLUSIONS

The principal conclusions from the tests are:

1. The standard method of molding and capping concrete cylinders with machined base and cover plates gave uniformly high strength equal to or greater than that from any of the other methods.

2. Deflection of the table of the testing machine used was small and had practically no effect on the test results.

3. For reliable results the use of the adjustable block with spherical bearing surfaces was found to be essential. A spherical bearing block with hardened steel balls between the spherical surfaces gave essentially the same results as the plain spherical block.

4. No difference in results was found when spherical bearing blocks were used in the following positions:

(*a*) On top of cylinder;
(*b*) Inverted on top of cylinder;
(*c*) Beneath the cylinder;
(*d*) Both on top and beneath the cylinder.

5. Small errors ($\frac{1}{4}$ in. or less) in centering the bearing block on the cylinder had little or no effect on the test results. An error of $\frac{1}{2}$ in. in setting, gave strength-ratios of about 90 per cent for 1:5 and 1:3$\frac{1}{2}$ concrete.

6. Cylinders molded on a plane cast-iron base and with top trowelled smooth, showed the following results when tested as indicated:

(*a*) With thin caps of gypsum or mixtures of cement and gypsum, the results were essentially the same as those obtained for the standard method of capping.

(*b*) Without bedding, the strength-ratios obtained were about 95 per cent for 1:7 concrete, 94 per cent for 1:5 concrete and 80 per cent for 1:3$\frac{1}{2}$ concrete.

(*c*) With sheet materials between top of cylinder and the spherical block, the strength-ratios obtained were less than 100 per cent for all of the materials used.

(*d*) For the sheet materials, the best results were obtained with Beaver Board, which gave strength-ratios of about 100 per cent for 1:7 and 1:5 concrete and about 90 per cent for 1:3$\frac{1}{2}$ concrete.

(*e*) For white-pine board, mill board and leather, the strength-ratios ranged between those found for Beaver Board and those found for no bedding (see (*b*) above).

(*f*) For the other sheet materials, blotting paper, sheet lead and rubber, the strength-ratios were less than those found for no bedding.

(*g*) The lowest strength-ratios were found for the $\frac{1}{16}$-in. sheet rubber; they were about 80 per cent for 1:7, 70 per cent for 1:5 and 50 per cent for 1:3½ concrete.

7. Cylinders made and capped by the standard method, tested with a ½-in. segment (circular segment of ½-in. mid-ordinate) of the cap removed, gave strength-ratios slightly less than 100 per cent. When a 1-in. segment was removed the strength-ratios obtained were 100 per cent for 1:7 concrete, about 95 per cent for 1:5 concrete and 90 per cent for 1:3½ concrete. The removal of a 2-in. segment gave strength-ratios of 90, 80, and 65 per cent for the three grades of concrete.

When the segments removed were replaced with 1:1 gypsum and cement mortar 3 hours before test, the strength-ratios were about 100 per cent except for the 2-in. segment, which showed strength-ratios of from 95 to 90 per cent.

8. Cylinders with plane parallel ends but with axes inclined, gave the same strength as standard cylinders for an inclination of ¼ in. in 12 in. and strength-ratios of about 92 per cent for an inclination of ½ in. in 12 in.

9. Cylinders with the top surface inclined showed strength-ratios of about 100 per cent for an inclination of ¼ in. in 6 in. and of about 95 per cent for an inclination of ½ in. in 6 in.

10. Cylinders molded with machined cast-iron plates so as to give convex ends and tested without bedding, gave pronounced reductions in strength even for a small amount of convexity. The reduction in strength increased with increase in convexity and with increase in the richness of the mix.

For a convexity of 0.01 in .the 1:3½ and 1:2 mixes showed strength-ratios of about 65 per cent and for a convexity of 0.05 in., about 40 per cent. For the 1:7 and 1:5 mixes the corresponding strength-ratios were about 80 and 55 per cent.

When tested with Beaver Board sheets at both top and bottom, the reductions in strength were about half as great as when tested without bedding.

The use of gypsum bedding for one group of cylinders with bases convex 0.05 in. gave strength-ratios of about 90 per cent.

11. The effect of concave ends was small compared to that of convex ends.

12. Sheared steel plates 8 in. square by $\frac{1}{4}$ in. thick, from warehouse stock, showed deviations from a true plane of as much as 0.012 in. Cylinders molded with these plates as bases and covers so as to give convex ends, gave results comparable with those from cylinders having the same convexity similarly made with machined cast-iron plates (see 10 above).

13. Tests with concrete of different consistencies using cylinders with ends convex about 0.01 in. showed similar results for all consistencies. The typical relation of strength to water-cement ratio was found.

14. The different conditions of test did not show a marked difference in the uniformity of the individual results. The average mean variation ranged from 4.1 per cent for one group of the standards to a maximum of 10.9 per cent for the cylinders tested without an adjustable bearing block.

15. Finally, the most important conclusion from these tests is that great care must be exercised when preparing cylinders for test in order to secure ends which are true planes. When the standard method of capping with plane cover plates cannot be followed, the cylinder should be trowelled smooth and bedded with a thin layer of gypsum or a mixture of gypsum and cement 3 to 6 hours before test. The cylinders should always be molded on a plane surface.

BIBLIOGRAPHY

"Notes on Resistance of Bricks to Crushing Force," by G. S. Greene, Jr., *Journal*, Franklin Inst., Vol. 65, p. 333, 1873.

Tests made on half brick using (1) 2 pieces of board $\frac{1}{2}$ in. thick; (2) a layer of sand; (3) packed with 2 pieces of cigar-box wood; (4) packed with sand.

"Report on Building Stones," Report of Chief of Engineers, U. S. Army, 1875, Appendix II, p. 29.

"Testing Materials of Construction," by W. C. Unwin, Published by Longmans, Green Co., New York, 1888, p. 416.

Discusses the diminution of crushing resistance of stone bedded on lead, and between millboards. The following forms of bedding were used: One plate of lead on each face, three plates of lead on each face, one plate of lead on each face $\frac{1}{8}$ in. smaller than face all around, between 2 millboards on each face, and cemented between 2 strong iron plates with plaster of Paris. (Lead plates 0.085 in. thick.)

"Compressive Resistance of Freestone, Brick Piers, Hydraulic Cements, Mortars and Concretes," by Q. A. Gillmore, Published by Wiley & Sons, New York, 1888, p. 2.

Tests made on stones which were of tough, medium and soft texture, using steel, wood, lead and leather for bedding. Values obtained were:

		STEEL	WOOD	LEAD	LEATHER
Tough		100	94	65	60
Medium		100	82	65	63.5
Soft	Sebastopol limestone	100	100	100	100
	Drab-colored sandstone	100	100	100	.....
	Massillon sandstone	100	110	90	59.4
	Massillon sandstone	100	103	85	.....

"Materials of Construction," by J. B. Johnson, Published by Wiley & Sons, New York, 1914, p. 354.

Capping of specimens recommended with plaster of Paris, using sized paper between capping and specimen to prevent absorption of water by specimen, which reduces strength of the material if it has a high absorption. Small load put on specimen while plaster is soft and left on for 10 min. or longer, until bed is hardened, when test proceeds to failure. Single thickness of tar-board recommended, but no material which will flow (such as lead) or spread (as wood). Ground surfaces also recommended. Graph shows effect of bedding with lead and also with plaster of Paris on strength of concrete.

"Treatise on Masonry Construction," by I. O. Baker, Published by Wiley & Sons, New York, 1899, p. 9.

Relative crushing strengths of pressing surfaces as follows: Steel 100, wood 89, lead 65 and leather 62.

"Spherical Bearings," by M. Schuyler, *Proceedings*, Am. Soc. Testing Mats., Vol. 13, p. 1004, 1913.

Examples of different bearing surfaces shown and discussed.

"Capping for Compression Specimens," by H. D. Foster, *Journal*, Am. Ceramic Soc., Vol. 6, p. 623, May, 1923. *Engineering News-Record*, Vol. 90, p. 1003, June 7, 1923.

Compressive strength tests made on tile capped with unretarded gypsum, with neat portland cement, with mixture of 3 parts by volume of portland cement to 1 part of unretarded gypsum, and on tile whose bearings were ground. Tile whose bearings were ground gave highest results. Results based on workability, yielding of cap, and influence of bearing block.

"Effect of Irregular Ends on Concrete Test Cylinders," by D. V. Terrell, *Engineering and Contracting*, Vol. 60, p. 228, August 1, 1923.

Tests indicate (1) that test cylinders should be 10 in. long; (2) that no attempt be made to finish the ends; (3) that they be capped after they reach the laboratory; (4) that all caps be at least 7 days old.

"Effect of Imperfect Ends on Compressive Strength of Concrete Test Cylinders," by D. V. Terrell, *Kentucky Road Builder*, March, 1923. *Engineering and Contracting*, Vol. 59, p. 984, May, 1923.

Methods of testing 1:2:4 concrete given: (1) concrete with neat cement, cut off with straight-edge and made nearly perfect as possible; (2) finished with trowel leaving uneven ends; (3) sheet lead placed over tops of rough cylinders to take up unconformities in cylinder; (4) Beaver Board used instead of sheet lead; (5) capped with plaster of Paris and placed under 2000-lb. pressure until cap set and then broken. Best results were obtained in the following order: 1, 5, 2, 4, 3.

DISCUSSION

Mr. Freeman.

Mr. P. J. FREEMAN.[1]—The author of the paper has given us a lot of information well worth careful study, but one or two matters of caution should be pointed out under Conclusion No. 4 (*b*). It is here stated that no difference in results is obtained when the head of the bearing block is inverted on top of the cylinder. This would be the case with the apparatus shown in Fig. 2 of the paper, but would not be correct for many spherical blocks which are now in use in testing laboratories. Such bearing blocks have the bottom part often several inches deep with a small upper or spherical part so that if the block is inverted you must certainly get an eccentric load. The radius of the spherical ball shown in Fig. 2 is at the surface of the block which is the correct thing to have and all spherical heads should be so designed, but I feel quite sure that the spherical blocks in half of the laboratories over the country are very different from the one used by Mr. Gonnerman, and if such blocks are inverted, unsatisfactory results will be obtained.

Conclusion No. 4 (*c*) states that no difference in results is obtained if the specimen is placed on top of the spherical block. It is possible to obtain satisfactory results with the head beneath the cylinder but not probable, for the reason that it requires extreme care to avoid producing an eccentric load. If the specimen is tipped over on the spherical block and the moving head hits a corner, such as will happen in any case excepting when the top of the specimen is exactly parallel to the moving head, the corner of the specimen will be sliced off. So I feel that we ought to put in a word of caution, for it is easier, as a rule, for many laboratories which have large and heavy spherical heads, to place the specimen on top. The requirements of our Society for testing require that the spherical block shall be on top of the specimen which is the only way to have it when large numbers of specimens are being broken by average operators.

I am very much interested in Conclusion No. 10 on convexity. I found some years ago that sheared plates would cause trouble because they were not flat. I think we should point out that it is quite possible to get this same convexity in a field specimen that has a large pebble occurring near the top of the specimen even though one

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[1] Chief Engineer, Bureau of Tests and Specifications, Department of Public Works, Allegheny County, Pa.

Mr. Freeman. is careful to cap the end with plaster of Paris and cement. I believe it is worth while to chip the pebble down so that it is at least flat or preferably concave; as Mr. Gonnerman points out concavity will not lower the strength.

Mr. Gonnerman. MR. H. F. GONNERMAN (*Author's closure by letter*).—The author agrees with Mr. Freeman that the conclusions drawn from the tests with the spherical bearing block in different positions might not apply to all types of bearing blocks. It was not intended that the conclusions drawn should apply to bearing blocks other than the type used. He also agrees that the practice of testing with the spherical bearing block beneath the cylinder should be discouraged.

The last sentence in Mr. Freeman's remarks conveys the impression that concave ends will not lower the strength. Concave ends will give a reduction in strength but this reduction is much less than that obtained with convex ends.

METHODS OF SECURING SAMPLES OF COMPLETED PAVEMENTS, WITH REFERENCE TO THE DETERMINATION OF THE QUALITY OF THE CEMENT-CONCRETE FOUNDATION[1]

By E. E. Butterfield[2]

There are times, when, in addition to the reports of the field engineering and inspection force as to the quantities of materials entering into the construction of a pavement, it is necessary to obtain an independent report on the quality of the finished product and of the quantities of its constituent materials.

When the compressive strength is to be taken as the index of the quality of concrete there is no considerable difficulty in obtaining and testing samples or in the interpretation of the results. It is true that there are many factors which have to be taken into consideration, such as the question of mechanical injury to the hardened concrete in the course of its removal and preparation into suitable test specimens, the conditions of curing of the original concrete in mass, the amount of water used in the mix, the age, the size and shape of the specimens, as well as the number and size of the samples in relation to the size of the job. Nevertheless, if the compressive strength is found to be that of concrete of the class specified, the consideration of these factors affecting the compressive strength does not give rise to any serious complication. If, however, the compressive strength of the concrete is below that of the class specified, then the question of a deficiency of cement arises and has to be approached by analytical methods. Here, the difficulties are many. The problem is beset with pitfalls and is open to manifold errors in method as well as in the interpretation of results. In regard to analytical treatment of concrete this communication lacks the degree of finality toward which one strives in scientific work, but it will serve to point out sources of error which may be avoided and to indicate the lines along which progress may be made in arriving at a method for the estimation of the original quantities of materials in hardened portland cement concrete.

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[1] From the Laboratories of the President of the Borough of Queens, New York City.

[2] In Charge of Laboratory, Borough of Queens, New York City.

METHODS OF SECURING SAMPLES

The Core-Drill.—If it is not necessary to obtain large samples of the concrete for study and analysis, the core-drill may be used to obtain samples of both the sheet asphalt and binder course and the concrete foundation. With a core drill in good condition it is possible to cover considerable ground in a day. The successful drilling of the sheet asphalt and binder course is a different problem from the drilling of hardened concrete and the success of the operation depends upon several details of set-up and manipulation. Before describing the drill and its accessories and the operation of drilling, we will discuss the difficulties in drilling sheet asphalt and asphaltic binder course, and the methods of overcoming these difficulties. Owing to the susceptibility of sheet asphalt to temperature, its behavior under the drill in summer and in winter is quite different.

Sheet Asphalt in Warm Weather.—It is very difficult to drill sheet asphalt with a shot bit in summer and the cores are usually deformed and beveled upwards at the edges. This is overcome by the use of a special cutting tool, known as a Davis cutter, which may be screwed on to the core barrel in place of the shot bit. The cutter has eight teeth of hardened steel alternately pitched in and out. It is operated without shot feed, but water is fed as in the case of a shot bit, only in somewhat greater quantity. With the use of the cutter it is possible to drill 1 to 1½ in. of sheet asphalt in warm weather in 5 to 10 minutes. The cutter will not drill the binder course without considerable loss of material in the core and considerable wear on the cutter; so before the binder course is reached, the cutter is removed, the shot bit replaced and the drilling continued. Round shot, however, is not used; angular and sub-angular fragments of crushed steel, technically known as "No. 14 Diamond Crushed Steel," are used. This results in smoother drilling and less surface irregularity in the cores. The asphaltic binder course may be regarded as an asphaltic concrete made of ¾-in. coarse aggregate and a "mortar" composed of asphaltic cement, sand and limestone dust. Owing to the difference between asphaltic cement and portland cement, the binder course does not possess the hardness and rigidity of portland cement concrete. Hence the necessity for great care in drilling. The object is to obtain in one piece an intact core of sheet asphalt and binder, with intact top and bottom surfaces. In order to do this, it is necessary to stop drilling about every ¼ in. when going through the binder course and probe with a cold chisel or large screw driver to see if the binder course is still firmly attached to the concrete. In this way it is possible to remove the core of sheet asphalt and binder course as soon as the binder is completely penetrated. If the core, separated from the concrete, is allowed to revolve within the shot bit on the surface of the concrete, there is usually much abrasion and loss of binder course from the core, as well as mechanical interference with further drilling from pieces of binder stone falling into the drilled groove in the concrete. chipping the edges of the top of the concrete and danger of spoiling both the bottom of the asphalt and binder core and the top of the concrete core.

Sheet Asphalt in Cold Weather.—The Davis cutter is not used in cold weather. In fact, when the temperature is around 32° F. the sheet asphalt becomes so hard and brittle that it tends to chip and spall. Drilling throughout is done with the shot bit and crushed steel chips, the same precautions being taken with the binder course as in drilling binder in warm weather.

Concrete.—The drilling of concrete with a $5\frac{1}{2}$-in. shot bit and crushed steel is a very simple operation. After the sheet asphalt and binder core is removed, the drill hole is cleaned, fresh crushed steel thrown in and the drilling through the concrete is carried on without interruption. Six inches of 1:3:6 concrete may be drilled in from 14 to 25 minutes, usually within 20 minutes.[1] Occasionally the cores break. The most frequent cause is the presence of large pieces of coarse aggregate in the path of the drill packed in so closely that only a thin layer of mortar is found between them. If a larger bit were used, say 8 in. in diameter, this would probably not occur. A $5\frac{1}{2}$-in. bit is somewhat too small for concrete containing commercial $1\frac{1}{2}$-in. stone with pieces of a maximum diameter of $2\frac{1}{4}$ in. However, a much heavier and more expensive drill would be necessary to carry an 8-in. shot bit, and as the occurrence of broken cores is infrequent and accidental, it is more economical and convenient to use a $5\frac{1}{2}$-in. drill, and when a core breaks to pull up and start drilling again within a few feet of the site of the fractured core.

Description of Drilling Equipment.—The manufacturers' catalogues, particularly Dobbins and Ingersoll-Rand, contain complete description of core-drills, so I shall confine my remarks to the method of mounting the drill and to modifications which have proved of great value in the operation of the drill. In drilling pavements on an economical basis there are certain conditions to be fulfilled:

1. The outfit should be as simple and compact as possible so that it may be moved easily and rapidly from place to place.

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[1] A plain or reinforced-concrete pavement presents no especial difficulties. A 1:1.5:2.5 concrete with trap rock aggregate and 100 lb. of reinforcing metal per 100 sq. ft. may be drilled as rapidly as a 1:3:6 concrete foundation.

2. The drill spindle must be free from extraneous movements, lateral, or up and down, and must rotate smoothly, evenly and truly about its axis.

3. It must be possible to interrupt the drilling, in the case of asphalt and binder, to hoist the drill parts, examine the hole and continue the drilling with a minimum loss of time.

4. The crew should be as small as is consistent with expeditious work.

Method of Mounting.—The drill, a class G-31 Ingersoll-Rand drill, and a two-cylinder Le Roi gasoline engine were mounted on a W. and K. 3-ton trailer. The trailer was equipped with disk steel wheels and solid rubber tires. The trailer is towed by a Fordson tractor. This arrangement is more convenient and economical than tying up a truck for the exclusive use of the drill. When the drill is not being used, the tractor may be used for other work.

Elimination of Vibration.—The closer the rotating mechanism is to the ground the smaller the chance of eccentric motion. The trailer frame on which the drill is mounted is 42 in. from the ground which is lower than many trucks. The springs of the trailer are immobilized by the insertion of solid oak blocks. Two trench jacks bolted at the top to a channel iron which in turn is bolted to the trailer frame between front and rear wheels, eliminate vibration from the front wheels and their solid rubber tires. The rear wheels are chocked with solid oak wedges. Most important of all, however, is a heavy oak guide block. The block is 14 by 20 in. and 4 in. thick, with a circular hole just large enough to permit free up and down movement and rotation without binding of the drill bit. The guide block is fastened by means of two angle irons to the rear truck of the trailer and the bottoms of the angle irons are braced at 45 deg. to the rear truck frame and also to the rear axle clips. The guide block is 9 in. from the ground. With these precautions the elimination of vibration is so complete that there is no visible movement of the trailer; and to the hand resting on the trailer frame there is a scarcely perceptible vibration when the drill is operating at full speed.

Stopping and Hoisting.—The ratchet lever for guiding the drill is reversible, but as the reversal takes time, we set the lever for downward movement only and then attached an iron crank to the nut on the free end of the lever shaft. The crank is used for a quick reverse and the ratchet lever for drilling only. The hoisting mechanism consists of two pieces of $1\frac{1}{2}$-in. pipe 8 ft. long connected by elbows and a cross piece at the top to which a block and fall is attached. The lower end of the block and fall is attached to the hanger of the water swivel. It is possible to stop, reverse, hoist, examine the drill hole, and start drilling again in less than one minute.

Crew.—One operator stationed at the drill lever, belt clutch, and water control; one helper to start the engine, watch the drill hole and feed the crushed steel; and one chauffeur to drive the tractor and also give hand in making hose connection with fire hydrants and blocking up the trailer, are more than adequate for the work. In fact we have done a lot of drilling with one operator and a chauffeur, the chauffeur acting as helper during the drilling operation. It will also be noted

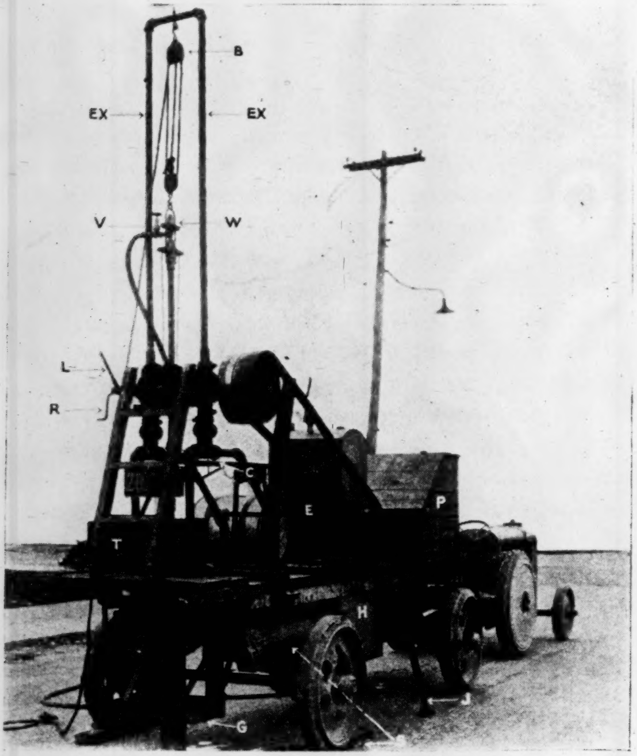

FIG. 1.—Drilling Equipment Mounted and Ready for Operation.

B	Block and fall
Ex	Extension rods
W	Water swivel
V	Water valve
L	Ratchet lever
R	Reverse crank
G	Guide block
S	Chock blocks
J	Trench jack
H	Hose box
C	Belt clutch
E	Engine
T	Tool box

that we have attached a valve between the hose connection and a simplified water swivel of our own design. There is no reason for feeding crushed steel through the water swivel when the maximum depth of hole is generally 9 in. The crushed steel is fed by hand directly into the annular groove in the pavement by the helper on the ground. The operator controls from the trailer platform, within an arm's length, the drill lever, the valve regulating the flow of water, and the clutch of the belt driving the drill.

The drilling equipment, mounted and ready for operation, is illustrated in Fig. 1.

Measurement of Cores.—The cores may be measured with a 12-in. vernier caliper, taking measurements at various points between intact surfaces, or they may be measured between two straight edges applied to top and bottom surfaces. The asphalt and binder must show smooth asphalt top and intact binder course on the bottom. The concrete cores must be intact on the top surface and should show adherent subgrade material on the bottom. It is also advisable to measure the depth of the hole. To do this, the drilling is continued well into the subgrade, at least 2 in., the hole is flushed with water and the subgrade material is dug out from under the concrete, for a sufficient distance to permit the application of a caliper jaw to the extent of 1 to 2 in. to the under surface of the concrete. Owing to the manner in which binder course and concrete sometimes interlock, the measurement of the depth of the sides of the hole may be less than the sum of the measurements of asphalt and binder core and concrete core.

Preparation of Concrete Cores for Testing.—The cores are placed in 14-gage galvanized iron molds and capped just to the level of the highest point of the surface with neat cement. They are then tested in the compression machine 24 hours after capping.

Removal and Treatment of Slabs of Completed Pavements.—If a detailed study of the structure and composition of the concrete is to be made, the specimens obtained with the core drill are not as satisfactory to work upon as slabs, cubes, or prisms sawed and finished to accurate dimensions. Rough slabs from 4 sq. ft., upward in size may be removed by the use of asphalt cutting tools on the sheet asphalt and bull-nose punches and sledges on the concrete. This work is usually done by an asphalt foreman and gang as it is easy to inflict considerable damage to the concrete by unskilled operation. If the slab of sheet asphalt and binder course measures 4 sq. ft., the concrete slab will be smaller owing to the wide and irregular cuts in the concrete made by the punches and sledges. Slabs over 4 sq. ft. are difficult to handle on account of their weight. With slabs less than 4 sq. ft. there is danger of producing artifacts in the concrete during its removal, handling and working into symmetrical test specimens.

Preparation of Test Specimens.—The rough slab of concrete is sawed into the desired shapes with a carborundum saw or diamond saw. For this purpose we use a planer-type combination saw, with interchangeable carborundum teeth blades or diamond teeth blades. The table is 6 ft. long and 30 in. wide. The head is equipped with ball bearings and will carry either two carborundum or two diamond saw blades of 30-in. diameter. The two saw blades may be spread apart 24 in. and be brought together to 3 in. between blades. This enables us to make two cuts in one operation, reducing the time of sawing proportionately. The table has four different feeds and a fast return. A 15-h.p. electric motor is the source of power. For most work the carborundum teeth blades suffice. In the case of trap-rock aggregates and some quartz aggregates it is advisable to use the diamond teeth blades. After the specimens are sawed to approximate dimensions, they are finished to exact dimensions on the rubbing bed.

Shape of Test Specimens.—For the determination of the weight per cubic foot and the compressive strength, a 4-in. cube is a convenient size. It is necessary, of course, to use a correction factor for the compressive strength of 4-in. cubes as compared with standard test specimens having a height of twice their diameter. We believe this procedure is preferable to use of prisms with a ratio of 2:1 between height and diameter. On account of the limiting thickness of 6 in. on the slabs it is necessary to make some concessions to standard practice. It is difficult or impossible to cut out of a 6-in. slab a specimen with greater face than 4 by 4 in. or at most 4.5 by 4.5 in. If a smaller dimension than 4 by 4 in. of bearing surface or 4-in. diameter is chosen, it is out of proportion to the size of the coarse aggregate, which in our locality is generally $1\frac{1}{2}$-in. stone or gravel containing pieces up to $2\frac{1}{4}$ in. in size. If 4 by 8 in. prisms are used they will have to be cut with their long axis parallel to the surface of the road. The compressive strength in that direction is lower than it is in the direction perpendicular to the road surface. H. Eltinge Breed first called our attention to this fact in a series of tests which he made for us. The average results on 4-in. cubes, which were oriented and tested according to their relation to the road surface, were as follows:

	DIRECTION OF APPLICATION OF LOAD WITH REFERENCE TO ROAD SURFACE	
	PERPENDICULAR	PARALLEL
Compressive strength, lb. per sq. in. (average of 16 cubes)	1705	1293

The 4-in. cubes may be used (1) for the determination of the weight per cubic foot of the air-dry concrete, (2) for the determination of the ratio of surface area of coarse aggregate to concrete, (3) for the test of compressive strength, (4) for securing samples of mortar from the crushed specimens and (5) for dehydration experiments on the crushed material. Tests Nos. 1, 2, 3 and either 4 or 5 may be made on each cube with the preservation of accurate data on volume and weight relations. For more rapid work in the study of surface relations between coarse aggregate and mortar, it is convenient to saw sections from the original rough slab, the full depth and length of the slab and from 2 to 3 in. wide. A large amount of flat surface may thus be secured for study.

ANALYTICAL TREATMENT OF CONCRETE

When the values for the compressive strength of the cores or cubes, corrected to the standard height-diameter ratio, fall below the values for concrete of the class specified, or when for any other reasons it is necessary to attempt to estimate the quantities of the original constituents of the concrete, then the analytical treatment must be undertaken. It seems to me that there is a definite need of recommended practice and uniform procedure for the principal classes of concrete and particularly for concrete made with quartz sand and limestone coarse aggregate. In one case, divided samples of the same materials were examined by six different laboratories. The reports on the proportions from the different laboratories varied from 1:2.28:5.92 in one laboratory to 1:5.7:14.3 in another, with others reporting 1:3:6 and 1:4.2:5.0. There is hardly any other field of analytical work where such wide variations could occur. This is due in part to the nature of the product, the materials and the problem, the unmeasured changes in volume which take place when loose materials containing 30 to 50 per cent of voids are mixed together, the bulking of fine aggregates with varying degrees of moisture and the inadequacy of bulk measurements with respect to the volume of solids and the weight of the solids. But the varying results of analyses are also due to lack of standard or uniform procedure for sampling and testing. It would seem that, with a number of slabs of concrete 4 ft. square and 6 in. deep and with the necessary equipment for preparing dimension specimens, one should at least be able to find a relation between the surface of coarse aggregate and the volume of coarse aggregate in the unit volume of concrete. If the volume of coarse aggregate can be determined with sufficient accuracy, then from the average weight of the concrete per cubic foot determined on symmetrical specimens and from analysis of the mortar, it should be possible to calculate the weights of materials per cubic foot of concrete. These weights divided by the average weights per cubic foot of the materials measured loose, should give the volumes of materials by bulk per cubic foot of concrete, within the limits of the variations which may have occurred in the unit weights of the original sand and the stone. We are not, by any means, in a position to propose or recommend a method which will do all of these things, but we have made experiments and analyses on known mixtures which may lead to the consideration of uniform procedure for the analytical treatment of concrete containing quartz sand as the fine aggregate and limestone as the coarse aggregate.

Methods Employed.—We have made different mixes, about 1 to 2 cu. ft. to a batch, using standard measures and weighing the loose volumes of the materials and of the entire batch. The cement and water were always weighed. The customary 94 lb. per cu. ft. was taken as the unit of cement. Materials from the same stock piles were used throughout. Repeated determinations on random samples gave average weights of 91 lb. per cu. ft. for the sand and 95 lb. per cu. ft. for the $1\frac{1}{2}$-in. limestone. The sand varied from 80 to 103 lb. per cu. ft. and the stone from 91 to 100 lb. per cu. ft. Each batch was molded into 6 by 12-in. cylinders, by the standard method, usually six to a batch. The forms were removed at the end of 48 hours, and the cylinders were stored in damp sand for 26 days. They were weighed at 48 hours and at 28 days. Three cylinders were tested at 28 days for compressive strength. The mortar from the crushed cylinders was used for analysis. The three remaining cylinders were stored under room conditions and allowed to come to constant weight. One or more of these cylinders was then sawed longitudinally with two saw cuts, yielding a central slab and two cylinder segments, in all four flat surfaces for measurement of areas in the proportion of about 250 sq. in. per cylinder of 340 cu. in. The estimation of areas was made by planimetric measurements on photographs of the sawed surfaces. The calcium oxide content of the air-dry mortars was determined gravimetrically on material comminuted to 80-mesh, using a double precipitation. The samples of mortar for analysis weighed 300 g.

A series of experimental mortars was made up according to Arthur N. Talbot's method[1] for mortar voids for the purpose of comparing the analytical properties of the hardened mortars with the known composition of the fresh mortars. The sand-cement ratio by absolute volume was varied from 2 to 6.5, corresponding to bulk proportions of cement to sand from 1:1.5 to 1:5.1. The properties of the fresh mortars are given in Table I and the properties of the same mortars in the hardened state, air-dry condition, are given in Table II. The whole batch of wet mortar, containing the excess of water over and above the water added at the point of maximum density as noted in Table I, was placed in a cylindrical tin mold with a solid bottom, tamped and allowed to set. When the mortar was sufficiently hard, the mold was removed and the mortar exposed to laboratory air until it came to constant weight. It received one drying in the oven at 105° C., usually when it was about two weeks old. The apparent specific gravity of the hardened mortar was calculated from its measured volume and its final weight. The apparent specific gravity of the mortar fragments, which weighed from 1 to 35 g., was determined by weighing in air, then coating with paraffin and weighing in water, making the necessary corrections for the weight of the paraffin and the suspension thread. Mortar fragments so treated did not gain weight during immersion in water for 20 minutes. The specific gravity and the ratio of soluble to insoluble

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[1] "A Proposed Method of Estimating the Density and Strength of Concrete and of Proportioning the Materials by the Experimental and Analytical Consideration of the Voids in Mortar and Concrete," *Proceedings*, Am. Soc. Testing Mats., Vol. 21, p. 940 (1921).

TABLE I.—PROPERTIES OF FRESH MORTAR PROPORTIONED BY TALBOT'S METHOD FOR MORTAR VOIDS.

Specific Gravity of Cement = 3.15. Specific Gravity of Sand = 2.67. Volume of Mold = 361 cc.

No.	Ratio of Absolute Volumes of Sand to Cement	Weight Ratio	Bulk Ratio (Dry Sand)	Weight of Sand, g.	Weight of Cement, g.	Volume of Sand, (measured), cc.	Volume of Cement, cc.	Weight of Water, Maximum Density, g.	Weight of Water, End Point, g.	Volume of Batch	
										Maximum Density, cc.	End Point cc.
1.....	2.	1:1.7	1:1.5	642	380	375	252	140	150	529	535
2.....	2.	1:1.7	1:1.5	642	380	375	252	140	150	535	544
3.....	2.5	1:2.2	1:1.9	689	319	410	212	130	135	521	532
4.....	2.5	1:2.2	1:1.9	689	319	410	212	130	135	522	532
5.....	3.	1:2.5	1:2.3	723	284	425	189	125	135	523	534
6.....	3.	1:2.5	1:2.3	723	284	425	189	125	135	520	528
7.....	3.5	1:3	1:2.7	750	249	445	165	115	130	517	527
8.....	3.5	1:3	1:2.7	750	249	440	165	115	130	518	529
9.....	4.	1:3.4	1:3	771	227	450	151	120	135	519	530
10.....	4.	1:3.4	1:3	771	227	455	151	120	135	517	529
11.....	4.	1:3.4	1:3	771	223	460	148	120	138	513	527
12.....	4.5	1:3.9	1:3.4	789	203	465	135	120	130	521	531
13.....	4.5	1:3.9	1:3.4	789	203	465	135	120	130	520	530
14.....	4.5	1:3.9	1:3.4	789	203	465	135	115	133	513	529
15.....	5.	1:4.2	1:3.8	803	189	475	126	125	140	524	534
16.....	5.	1:4.2	1:3.8	803	189	475	126	120	135	521	530
17.....	5.	1:4.2	1:3.8	803	189	480	126	120	138	516	534
18.....	5.5	1:4.7	1:4.2	816	175	490	116	110	127	512	527
19.....	6.	1:5.1	1:4.6	826	162	495	108	110	127	516	529
20.....	6.5	1:5.5	1:5.1	835	152	515	101	115	132	527	541

material in the mortars after grinding to 80-mesh were determined by the standard method for the analysis of portland cement.

Discussion of Surface Measurements as Means of Estimating the Volume of Coarse Aggregate.—Just as it is possible to reconstruct a histological structure in three dimensions from camera lucida tracings of serial sections, so must it also be possible to determine not only the volume of stone in concrete but also to obtain a model of the sizes and shapes of the pieces of stone and their space relations to one another. But, in order to do this, we must first determine the number of sections and the thickness of the sections, in relation to a given volume of concrete, which are necessary to give an accurate reproduction. Starting from a definite volume of concrete which contains a known volume of stone and by having the concrete sawed into sections of different thicknesses, one may find empirically by planimetric measurements or tracings, the thickness of slab, the number of slabs and the amount of surface in relation to the volume of concrete which are necessary to give the same numerical figure for the surface ratio of

TABLE II.—PROPERTIES OF SET MORTAR PROPORTIONED BY TALBOT'S METHOD FOR MORTAR VOIDS.

Mortar of Table I examined in Air-Dry Condition.
CaO in Cement = 62.0 per cent. CaO in Sand = 0.17 per cent

No.	Age of Mortar, days	Measurements of Test Cylinder						Apparent Specific Gravity, Whole Specimen	Apparent Specific Gravity, Mortar Fragments	Specific Gravity, Ground Mortar passing 80-mesh	CaO, per cent by weight	Cement, per cent by weight calculated from CaO	Cement, per cent by weight from known weights of Mortar and Cement	Ratio of Soluble to Insoluble Material
		Height, in.	Diameter, in	Area, sq. in.	Volume		Weight, g.							
					cu. in.	cc.								
1	25	4.576	2.986	7.002	32.041	525.1	1056.3	2.012	2.038	2.602	22.15	35.66	36.0	1:1.4
2	22	4.605	2.995	7.046	32.447	531.7	1076.4	2.024	2.025	2.601	22.14	35.65	35.3	1:1.3
3	20	4.560	2.984	6.993	31.888	522.6	1038.	1.986	2.029	2.602	19.18	30.88	30.7	1:1.7
4	19	4.557	2.980	6.975	31.785	520.9	1048.9	2.014	2.013	2.615	19.39	31.22	30.4	1:1.7
5	25	4.599	2.974	6.946	31.945	523.5	1032.1	1.971	1.992	2.602	17.39	28.00	27.5	1:1.9
6	22	4.514	2.978	6.965	31.440	515.2	1046.2	2.036	2.024	2.601	17.31	27.87	27.1	1:1.9
7	20	4.534	2.985	6.998	31.729	519.9	1021.8	1.965	1.981	2.620	15.31	24.65	24.4	1:2.3
8	19	4.528	2.975	6.951	31.475	515.8	1029.2	1.995	1.989	2.615	15.42	24.83	24.2	1:2.2
9	25	4.480	2.973	6.942	31.100	509.6	1009.1	1.980	1.993	2.608	14.32	23.06	22.5	1:2.5
10	22	4.516	2.975	6.951	31.391	514.4	1026.9	1.996	2.000	2.601	14.29	23.01	22.1	1:2.4
11	24	4.482	2.974	6.946	31.132	510.2	1017.	1.993	1.964	2.622	13.87	22.33	21.9	1:2.7
12	20	4.500	2.958	6.872	30.924	506.8	1010.6	1.994	2.001	2.628	12.35	19.88	20.1	1:2.9
13	19	4.529	2.993	7.036	31.866	522.2	1019.5	1.952	2.013	2.635	13.13	21.14	19.9	1:2.8
14	24	4.542	2.970	6.928	31.467	515.7	1011.	1.960	1.958	2.623	12.29	19.79	20.1	1:3.0
15	22	4.470	2.977	6.950	31.067	509.1	1004.6	1.973	1.979	2.617	11.79	18.98	18.8	1:3.0
16	27	4.550	2.988	7.012	31.905	522.8	1011.8	1.935	1.963	2.601	11.97	19.27	18.7	1:3.0
17	24	4.530	2.983	6.989	31.660	518.8	1011.5	1.950	1.948	2.623	11.56	18.61	18.7	1:3.2
18	24	4.475	2.980	6.975	31.213	511.5	1009.	1.973	1.981	2.636	10.71	17.24	17.3	1:3.4
19	24	4.500	2.979	6.969	31.361	513.9	1000.	1.946	1.951	2.626	9.85	15.86	16.2	1:3.7
20	25	4.586	2.984	6.993	32.070	525.6	1010.	1.924	1.899	2.627	10.00	16.10	15.0	1:3.9

stone to concrete as the known ratio of the volume of stone to volume of concrete.

TABLE III.

Bulk Proportions from Individual Measurements of Materials in Each Batch	Bulk Proportions from Volume of Air-Dry Concrete and Average Weight of Materials from Stock Pile	Weight of Air-Dry Concrete, lb. per cu. ft.	Volume of Solid Stone, per cent	Surface Area of Stone, Planimetric, per cent	Difference between Area and Volume, per cent
1:1.5:2.5	1:1.6:2.4	150.3	40.9	42.6	+4
1:2.9:5.9	1:2.4:5.4	151.0	52.0	57.3	+9
1:3.0:6.0	1:3.3:6.0	149.2	49.4	49.1	−1
1:4.0:10.0	1:4.2:10.2	150.0	56.4	56.8	+1

Taking the 1:3:6 concrete in Table III as an example, let us compare the actual properties with the calculated results. The following materials were used:

Cement	23.50 lb.
Sand	74.25 "
Stone	142.00 "
Water	19.50 "

The mixture yielded 1.62 cu. ft. of air-dry concrete. Although 19.5 lb. of water was added, most of this has evaporated. From the study of the mortar voids series, it was found that the quantity of water remaining in the mortar at constant weight was about 10 per cent of the weight of the cement. This figure we have confirmed on numerous samples of neat cement blocks exposed to varying conditions of curing. Using 10 per cent of the weight of cement as an average for the amount of water of hydration in the air-dry concrete, we find the following composition:

Cement	14.48	lb. per	cu. ft.	of	concrete
Sand	45.77	"	"	"	"
Stone	87.53	"	"	"	"
Water	1.45	"	"	"	"
	149.23				

The average weight of three 6 by 12-in. cylinders was 149.2 lb. per cu. ft. Dividing the weights of materials in one cubic foot of concrete by the respective average weights of the materials, 94, 91 and 95 lb. per cu. ft., we find the bulk of materials in one cubic foot of concrete:

Cement	0.154 cu. ft.
Sand	0.503 " "
Stone	0.921 " "

and a bulk ratio of 1:3.3:6.0.

Treated from the analytical side we have 49.1 per cent surface area of stone in the concrete, which agrees within 1 per cent with the known volume of solid stone in the concrete. The stone has a specific gravity of 2.84, and a cubic foot of solid stone would weigh 177.2 lb. The weight of stone per cubic foot of concrete was 87.53 lb. or 0.494 cu. ft. of solid stone and since the cubic foot is our unit there would be 49.4 per cent solid stone by volume. Analytically we have found 149.2 lb. per cu. ft. as the weight of the concrete, 49.1 per cent surface area of stone, and 15.35 per cent CaO in the mortar. Using these figures we find $49.1 \times 177.2 = 87.0$ lb. of stone per cubic foot of concrete and $149.2 - 87.0 = 62.2$ lb. of mortar. The percentage of cement in the mortar is $15.35 \times 1.61 = 24.7$. The weight of the mortar, 62.2 lb., multiplied by the per cent of cement in mortar, 24.7, equals 15.4 lb. of cement, a figure which is too high due to the water of hydration in the mortar, but will serve as a basis for the water correction of 10 per cent of the weight of the cement. $62.2 - 1.5 = 60.7$ lb. dry materials in mortar. $60.7 \times 0.247 = 15.0$ lb. of cement. $60.7 - 15.0 = 45.7$ lb. of dry sand. The bulk relations may now be calculated from the weights of the materials in a cubic foot of concrete divided by the average weight of the materials in bulk:

	PER CUBIC FOOT OF CONCRETE
Cement	$15.0 \div 94 = 0.159$ cu. ft.
Sand	$45.7 \div 91 = 0.502$ " "
Stone	$87.0 \div 95 = 0.916$ " "

Bulk ratio = 1:3.2:5.8

Proceeding with the other cases in the same manner we find bulk ratios for the concretes in Table III of:

1 : 1.8 : 2.9
1 : 2.4 : 7.0
1 : 3.2 : 5.8
1 : 4.3 : 10.6

on the basis of the following determined percentages of CaO in the mortars, 22.3, 18.5, 15.4, and 12.1, respectively. When the volume of coarse aggregate may be estimated to ±1 per cent the results are in excellent agreement with the known proportions. A difference of +9 per cent or even +4 per cent in the volume of coarse aggregate results in proportions considerably leaner than the actual mix. A plus error in the estimation of coarse aggregate is cumulative, not only increasing the proportion of coarse aggregate but also reducing the numerical value for the cement which is calculated from the difference between coarse aggregate and concrete, either by weight or by volume. In the case where the planimetric measurement gave 9 per cent greater area of stone than the volume of stone in the concrete we have sawed other cylinders to determine if there is an unequal distribution of stone in the different cylinders. We have also tried to determine the quantity of stone in the other cylinders of the same set, which were used for the compressive strength, by mechanical separation of the crushed and dehydrated material. In heating 30 lb. of material at a time we had difficulty in preventing the calcination of the limestone if sufficient heat was used to loosen the bond of the cement. If the material was heated below the point of calcination a clean separation of the mortar was almost impossible. It is possible that the dehydration method may be applied on a large scale with an oven of proper design, but the labor involved in separating 30 lb. of dehydrated material is considerable and requires from one to two days of picking, scraping, and brushing the individual stones from the mortar. Due to the calcination of the limestone and its consequent breaking up into smaller fragments passing a $\frac{1}{4}$-in. screen the quantities of stone we obtained were 25 per cent less than the known quantity in the concrete.

As indicated in the beginning, our analytical results are not conclusive. When the area of stone measured on the surface of the concrete coincides with the actual volume of stone, concordant results are obtained for the estimated bulk proportions. An error of 9 per cent in the estimated volume of stone in a 1:3:6 mix results in proportions of a different class of concrete from the actual mix. If such a result is obtained on a small batch of absolutely known composition, it is quite apparent that much greater precautions and accuracy will be required in the examination of concrete from the structure. If such examinations are to be made and are to be of any value there should be a uniformity of procedure on the following steps:

1. The number and size of samples with reference to the quantity of concrete in the structure.
2. The quantity of surface area to be measured with reference to the unit volume of concrete, if surface measurement is to be used as a method of estimating the volume of stone.
3. The methods of analysis of mortar.
4. The methods of calculation and expression of results.

We are continuing our experiments on known mixtures and when we have further information on the relation between surface areas and known volumes of stone in concrete we propose to proceed to job concrete mixed under known conditions.

DISCUSSION

Mr. Breed.

MR. H. ELTINGE BREED.[1]—I think Mr. Butterfield's able paper and his remarks in regard to it demand the consideration of every investigator in concrete on mixes of known characteristics. I have known pavement foundations which are in bad condition after a few years that should have lasted at least twenty years. Many of these were made of good materials under a good to fair specification, and the poor results are entirely due to ignorant supervision. With these failures staring us in the face we are more or less groping around trying by experiment, different methods, and visual examination, to get light on what has happened. So far we have had to be satisfied with the usual test for compression as an evidence of the quality of the concrete. What we need, as Mr. Butterfield has pointed out, are other methods of sampling, testing and analyzing, whose usefulness will be increased by their uniformity and standardization.

Mr. Butterfield has by his work advanced our knowledge along this line. There are two things that I should like to call attention to, which are open to standardization. One is the planimeter method of measurement of surfaces to determine the percentages of the respective aggregates which at the present time, from work that has been done in my office and from work of others which I have had access to, gives a wide range in results. That would seem to be something that we all could get together on and find some method which could be standard and which would help out our knowledge along these lines. Another point is, that from time to time results have been published giving coefficients which could be used in translating the compressive strength of cubes or cores to an equivalent value of the cylinder with a diameter length ratio of 1:2. Most laboratory cylinders are made with a ratio of 1:2, either 6 by 12 or 8 by 16 in. In taking cores from a pavement, if the pavement is only 6 in. in thickness, you could hardly be expected to get a 3 by 6 core and get adequate results, particularly as your coarse aggregate is sometimes $2\frac{1}{2}$ in. in size. It would be well if a number of the State Highway Departments who have been investigating the subject of pavements by taking cores, could compare their results, and from those results a coefficient could be worked out to translate these values.

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[1] Consulting Engineer and Director of Highway Engineering, New York University.

Mr. Butterfield called attention in his paper to compression tests made by me where greater compressive strengths were obtained when the test was made with the long axis of the major part of the coarse aggregate parallel to the surface of the pavement. The cubes in question were of foundation concrete made with gravel aggregate, of which a large part was of an elongated nature. The concrete had all the appearances of having had excess water used in mixing, and the arrangement of the stones from depositing and working corresponded to the position of gravel in the river bed. The increased strength here, I think, is analogous to a bond in a masonry wall. The increase shown was roughly in the neighborhood of 33⅓ per cent. The average of one-half the cubes was around 1750 lb. per sq. in. and the other half, taken vertically, was around 1250 lb. **Mr. Breed.**

It might be of interest to those of you who have thought something about core drilling to know a little about its cost on the basis of some observations I made in the Borough of Queens of the working of the machine that Mr. Butterfield has described in his paper. We figure that the cost of the cores is about $3.60 each. That is for 6 in. of 1:3:6 concrete topped by a 3-in. asphalt surface, with binder cores. If the concrete only is to be bored, that cost is reduced to approximately $2.25 or $2.50 per core, the labor being the major part or about 72 per cent of the total.

MR. R. W. CRUM.[1]—The thing that we find the hardest in studying this problem is the lack of published data of actual tests such as these. I think this method of estimating the amount of coarse aggregate has a great deal of promise and value. Mr. Butterfield referred to the use of the dehydration method as a means of comparison in his work. We have found the same difficulty with that particular method that he finds. In dehydrating the concrete, the nature of many coarse aggregates is changed to such an extent that the relative amounts of the fine and coarse aggregates as determined do not bear much relation to the original mixture. We have found that the dehydration method is very reliable on some siliceous gravels or sands which are not affected by the temperature that is necessary to get the cement separated from the aggregate. We have some hope of a reasonably good ultimate success in analytical treatment in separating the amount of cement from the total aggregate in a great many cases, although with the glacial type of materials, the sands and gravels are so complicated as to make chemical treatment quite uncertain at times. There are a number of research agencies at work on the problem at the present time and we may reach some kind of a reasonable process. **Mr. Crum.**

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[1] Engineer of Materials and Tests, Iowa State Highway Commission.

Mr. Howe. MR. H. L. HOWE, JR.[1]—It is becoming part of our regular routine in the laying of asphalt pavements to take sample cores from the finished pavements. We take these cores, in the first place, to determine the thickness of the various courses and to determine the weight of the material laid per square yard, and also as a check on the efficiency of rolling.

Our method is much simpler than the core drill methods and we believe that it takes practically as good a core. We have a small kit, about 1½ ft. long, in which we have a small hydraulic jack and some dies made out of about 3 in. outside diameter seamless steel tubing turned to a cutting edge on the outside at one end and hardened. We also have in the kit plugs of asphalt mixture just the diameter of the outside of these dies and a can containing a naphtha cut-back asphalt cement.

Our inspector takes this kit onto the street where a pavement is being laid, places the sharp end of the die at the point he wants to sample, runs the roller up, places the hydraulic jack on top of the die and jacks it right down to the concrete base. You can ordinarily take a sample from a 2 or 3-in. pavement in a couple of minutes. Before moving the roller the inspector paints the hole in the pavement with a naphtha cut-back asphalt cement, takes one of the pre-compressed plugs and jacks the plug into the pavement, thus leaving the pavement in as good condition as before the sample was taken, in about five minutes for the whole operation, at a very moderate cost.

We also use this method in taking samples in the study of old pavements that have proved to be particularly good, or that have been a failure. In such a case, instead of using a roller to jack against, we simply take a chain driven truck, that is, one having a solid axle without differential.

By analysis of the sample core we can determine the voids and study the type of dust filler, sand, stone, etc.

Mr. Butterfield. MR. E. E. BUTTERFIELD.—The methods we have employed are limited to one class of materials, that is, limestone coarse aggregate, Cowe Bay sand, which is predominately a quartz sand with a varying percentage of granitic material, and portland cement. We selected what we thought was the most difficult case, therefore the method would not have to be applied over the entire range of concreting materials. In the case of a purely siliceous aggregate, coarse and fine, other methods, such as the dehydration method, or purely chemical methods, may be employed, if anything is to be gained thereby in the saving of time, labor or expense. If the concrete is disintegrated, diamond

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[1] In Charge, Municipal Testing Laboratory, Rochester, N. Y.

Mr. Butterfield.

saws or carborundum saws cannot be used to advantage, because concrete which is so deficient in inherent stability that it cannot be drilled or removed in mass will not stand up with the action of the saws.

The sawing equipment which we have used consists of two parallel 36-in. saw blades, adjustable on a shaft, so that parallel saw cuts may be made from 1½ in. up to 24 in. apart. Diamond tooth blades and carborundum blades may be interchanged to meet the conditions, diamond blades for extremely tough aggregates and carborundum blades for aggregates of ordinary hardness and toughness. The sawing of concrete of reasonable stability is a very rapid and simple operation.

I am very much interested in Mr. Howe's results with what you might call a punch method, because the drilling of the sheet asphalt consumes more time than the drilling of the concrete. In our work we are not interested so much in the asphalt, apart from its thickness, because the daily laboratory control of the asphaltic mix has been more thoroughly and uniformly standardized than have been the conditions of inspection and testing 1:3:6 concrete foundation work. We are concerned primarily with the asphalt part of the pavement, in getting it out of the way, so that we may obtain representative samples of the underlying concrete. Any method which will facilitate the removal of the asphalt top, will also shorten the time and should decrease the cost of the entire operation.

A STUDY OF SIEVE SPECIFICATIONS

By Lewis V. Judson[1]

The specifications for the U. S. Standard Sieve Series were drawn up several years ago after a careful study of all the sieve data then available. It was realized then and has been stated from time to time that these specifications were subject to such changes as the increase in knowledge of sieves might show necessary. The considerable number of sieves tested in the past few years was one of the causes which led to a belief at the Bureau of Standards that the time was ripe to reconsider the specifications in some detail.

The question of a change of any specifications is one which needs a most careful study before the change is made. The new specifications may be intrinsically better than the old, and yet the change may not be a wise one to be made at the time when it is proposed. A consideration of vital importance with reference to specifications is their acceptance and use. That is, the general acceptance and use of a tolerably good specification is more to be desired than the nominal adoption of a perfect specification which is not generally acceptable, and is, therefore, not used.

A study of the specifications for sieves was recently made at the Bureau of Standards with a view toward making the U. S. Standard Sieve Series more effective. In this study it was sought, first, to ascertain the essential merits and defects of the specifications of the Bureau of Standards then in effect; second, to determine the main causes for the rejection of sieves under these specifications; third, to study other existing specifications; and lastly, to determine what changes, if any, should be made.

The advantages to be derived from the use of a series of sieves which progress in a geometric ratio are generally recognized and need no discussion here. The particular series adopted as the U. S. Standard includes a sieve having nominal openings 1 mm. square and also a sieve having nominally 200 wires to the linear inch. It may therefore be regarded as essentially metric, or as essentially based on the inch system, according to personal preference. In actuality, it is universal without losing any merits by its universality.

A series of wire diameters was selected which experience had shown to be best adapted for precision testing sieves, and which represented, as nearly as is practicable, existing sieve practice.

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[1] Associate Physicist, U. S. Bureau of Standards.

Most other series of sieves are found on analysis to be simply groups of sieves selected from the variety of sieves manufactured. One exception to this statement is the Tyler Series, in which the nominal openings are essentially the same as those of the U. S. Standard Sieve Series.

The requirement in the various sieve-using industries is that sieves be obtainable varying from these nominal dimensions only by a small amount necessitated by the sieve-making process. This variation must be sufficiently small as not to vitiate the results of the screening to be done with the sieves. Correspondence and tests at the Bureau of Standards showed that the sieve situation was not entirely satisfactory to either manufacturer or user and it seemed desirable to determine whether the specifications were too strict or whether the requisite care was not being used by the sieve manufacturers. As a basis for this work an analysis was made of the results of the sieve tests made at the Bureau of Standards.

The specifications as they were originally drawn up by the Bureau of Standards were based very largely upon a knowledge gained from the test of so-called 20, 30, 100 and 200-mesh sieves. Since 1916 a considerable number of sieves of all degrees of fineness have been submitted for test and it seemed probable that a study of this material would furnish valuable data.

It had appeared at first that the sieves of the U. S. Standard Sieve Series could be placed in five groups of nearly equal size, not only because it serves as a possible aid to the memory but also because the tolerance seemed to fall into such a grouping. From a survey of our data this grouping has been found to be undesirable for two reasons, first, the percentage tolerances on sieves coarser than No. 8 cannot be smaller than those on No. 8 to No. 18, inclusive, and, second, a 60-per-cent tolerance in maximum opening which seems very just for No. 140, No. 170 and No. 200 sieves is inadequate at the present stage of development of the weaving of the three finer sieves. That the first conclusion is true is shown by the rejection of nearly 90 per cent of the sieves coarser than No. 8, whereas the No. 8 and No. 10 are being manufactured so that a large majority meet the specifications. Only two No. 325 sieves have been tested which conformed to specifications, and very few No. 230 or No. 270. The chief cause for rejection was irregularity of weaving, some openings being from 60 to 90 per cent greater than the nominal value, while a few were greater than would be permitted under a 90-per-cent tolerance; so that 90 per cent seems to be a fair value. Every effort on the part of the manufacturers should be made to perfect the weaving of fine sieve cloth so that the 60-per-cent tolerance, which is the desirable aim in sieving work, though impracticable now, may be adopted later.

Since it seemed very desirable to determine whether or not the tolerances in average opening had been wisely chosen, a means was sought for correlating the measured dimensions of wire diameter and of opening and the actual sieving results obtained from standard sieving tests. These data were available for the No. 200 sieves only, which, however, are the most used of all sieves. Out of a list of several hundred No. 200 sieves of different makes tested during the last five years, it was found that only six sieves, certified as conforming to specifications, had correction factors of as much as 3 per cent as determined by standardization with standard samples of cement, and that the vast majority of the correction factors were between +2 per cent and −2 per cent. The interpretation of these results is that the specifications of the Bureau of Standards for the tolerance in average opening is a very just one for No. 200 sieves. From considerations of the relations of the tolerances on average opening as applied to other sieves of the series, it would seem that the revised tolerances of the Bureau, which are the same as those proposed by Committee E-1 on Methods of Testing of this Society and which vary only slightly from the tolerances previously in force, are as just as possible.

A search for any correlation of wire diameter with sieving value of No. 200 sieves gave a negative result. Indeed, there does not appear to be on record at the Bureau of Standards any results showing a variation in sieving value definitely ascribable to differences in wire diameter. Doubtless the diameter of the wire of a sieve does have its influence on the sieving results, but the variation in opening has such a marked effect that this masks the relatively slight effect due to the wire diameter. Large variations from the nominal wire diameter of the U. S. Standard Sieve Series, however, has been found by the Bureau of Standards to be disadvantageous: if the wires are too small they break too easily; if too large they tend to form pockets and cause the sieving operation to be a tedious one with results not as consistent as would be desirable.

Further investigation of the interrelation between measured physical dimensions of No. 200 sieves and their sieving values showed that a few excessively large openings in a sieve always produce a marked difference in sieving value, amounting in some cases to as much as 5 per cent. It also appears that the sieve correction for No. 200 sieves using standard cement has a tendency toward a plus value if the average opening between adjacent warp wires is greater than the average shoot opening, and a tendency toward a small negative quantity if on the average the rectangular openings have their greatest length between adjacent shoot wires. Of course this only holds for the limited range of average openings permitted by the tolerances, and it is possible that the sieving value is a function of the area of the opening and of the quantity, warp opening minus shoot opening. This question is now the subject of further investigation. Fig. 1, prepared from the original graphical representation of the data, is given rather to indicate that the question is worth further investigation than to prove any law relating the quantities involved. It is interesting to note in this regard that J. J. Griesenauer in his article on "A Sieve Test for Cement that Insures Uniformity in Fineness,"[1] called attention to the fact that by holding a sieve in such a manner that the cement always passed back and forth across the warp wires, a higher percentage passing the sieve was invariably obtained than when the test was made by sieving across the shoot wires. It seems probable that these results obtained at the Bureau of Standards, rotating the sieve in the usual manner, and the results

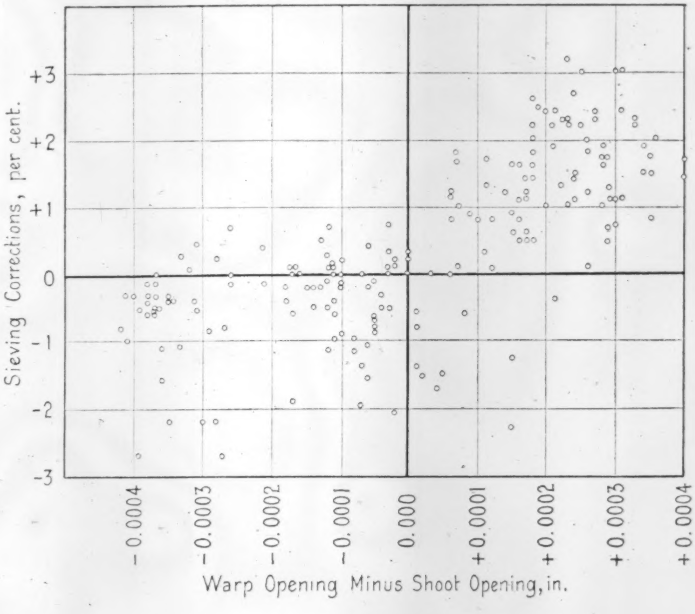

FIG. 1.—Sieving Corrections for No. 200 Sieves.

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[1] *Engineering News*, Vol. 70, p. 1296, December, 25, 1913.

found by Griesenauer, may be traceable to peculiarities inherent in the woven wire cloth.

From the studies which have just been discussed it appeared that several changes in the specifications were worthy of consideration. The fact that the Bureau's specifications on wire diameter were believed to be more rigid than was necessary formed a frequent point of attack against the specifications. To this was charged the failure of some users to get the sieves desired, while to it was also charged by manufacturers their failure to produce sieves conforming to the specifications. As a matter of fact the records of tests carried out at the Bureau of Standards show that there has been little difficulty, except in a few isolated cases, in obtaining any of the sieves with wires conforming to the tolerances in force at the Bureau of Standards for the past several years. Of the many sieves made by one concern which have been tested at the Bureau of Standards in recent years, not a single one has been rejected because the wires were not within the prescribed tolerance. The records of the tests of sieves of another manufacturer show only three rejections for wire diameter on sieves finer than No. 16 and only seven for coarser sieves. Other manufacturers have not been as successful as these two, but in every case, rejections because of incorrect openings far outnumber those due to the wire diameter being outside the specified limits. Hence, the real difficulty in securing sieves has been in getting the openings, both the average and the maximum in a sieve, to be within the specifications. Nor is this difficulty due, in the majority of cases, to the specifications being too strict. If No. 60 and No. 80 sieves are so made that nearly all of them conform to specifications, there does not seem to be any reason why No. 70 sieves, which are between them, should not conform to the same specifications. And yet there have been an excessive number of No. 70 sieves rejected, whereas the majority of No. 60 and No. 80 sieves which were submitted have passed.

The Bureau has devised an apparatus for testing sieves which is rather simple in construction. This apparatus, which was described in the *Journal of the Optical Society of America and Review of Scientific Instruments*,[1] consists of a projection apparatus, whereby the shadow of a wire may be thrown upon a ground-glass screen at a magnification of 250 times by the use of a 16-mm. microscope objective and an ordinary eyepiece. If sieve manufacturers would use such an apparatus the percentage of sieves rejected at the Bureau of Standards would be greatly reduced. Sieves are frequently submitted to the Bureau which can be rejected on inspection, indeed on an inspection that could just as well be made at the factory.

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[1] L. V. Judson and R. E. Gould, "Sieve Testing Apparatus," *Journal of the Optical Soc. of America*, Vol. VI, p. 719, September, 1922.

In Fig. 2 is shown a microphotograph with a magnification of 60 diameters of a portion of a sieve having some very large openings.

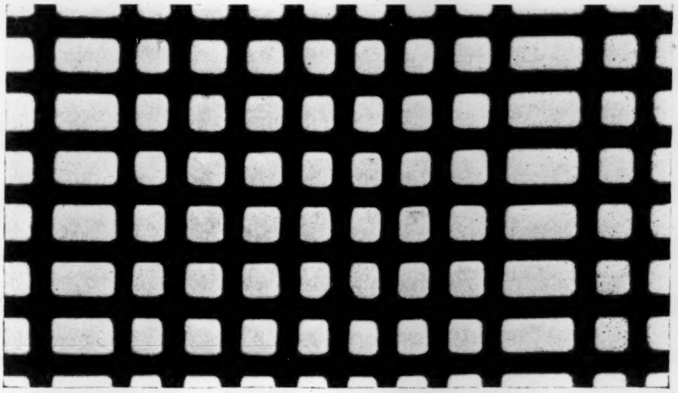

FIG. 2.—Defective No. 200 Wire Cloth (× 60). Note the Irregularity in Weave.

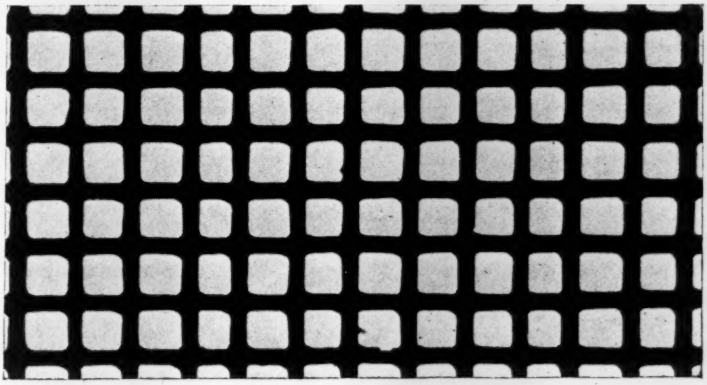

FIG. 3.—Certified No. 200 Wire Cloth (× 60).

Some sieves have been tested during the past year having large holes like these every tenth or twentieth of an inch.

This then was the situation in the early months of 1924: the nominal values for the U. S. Standard Sieve Series were subject to but very little adverse criticism; the tolerances of average opening of a few very coarse sieves, and of maximum opening for the three finest sieves, needed slight modification; the specifications were being severely criticized by some as having a tolerance in wire diameter which was too strict; and quite a few sieves were being rejected because of tolerances in average and in maximum opening which were generally admitted as just. As a result of the studies made at the Bureau of Standards and also of the discussion in several A.S.T.M. committees, notably the Sub-Committee, of Committee E-1, on Classification of Material According to Size, the Bureau adopted revised specifications on April 15. The present specifications of the Bureau of Standards and the proposed specifications of the above-mentioned subcommittee, now being recommended to the Society by Committee E-1,[1] are identical.

It is believed that the revised specifications are not only intrinsically better than those which they replace, but that their adoption is a wise step forward. The specifications have been strengthened at their weakest point, and the changes are of such a character that they do not invalidate any certificates already issued by the Bureau of Standards. A number of manufacturers have demonstrated that they can produce sieves of precision, a product the manufacture of which requires great skill and care. A unification of specifications, such as that which will result from the adoption of the same nominal values and tolerances by the Bureau of Standards and the various committees of the A.S.T.M., will mean that the users of sieves will be in a position to demonstrate that sieves are required which conform to definite published specifications, and the manufacturer will see that sieves of the character indicated by Fig. 2 are not furnished as precision testing sieves when those whose openings are even, as shown in Fig. 3, can be produced by exercising that care which is required in accurate work of this character. The ultimate results will depend upon the attitude of the manufacturers and users of sieves.

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[1] Report of Committee E-1 on Methods of Testing, *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part I, p. 697 (1924).

INFLUENCE OF DIAMETER OF WIRE ON PERFORMANCE OF SIEVES

By Duff A. Abrams[1]

Introduction

The American Society for Testing Materials defines a "screen" as an apparatus for separating sizes of material, in which the apertures are circular, and a "sieve" as one in which the apertures are square.[2]

Sieves and screens are used in many industries such as mining, metallurgical, construction, pharmaceutical, milling, ceramic, etc., for separating granular materials into different sizes or for determining the proportions of different sizes in graded materials.

In plant operation, where the purpose usually is to separate graded materials into different sizes, the size of screen or sieve opening necessary to secure the desired separation at the highest efficiency can best be determined by trial. These sizes may vary over a considerable range; since, for a given material, the size passing through or retained on a given clear opening depends on many factors, such as the rate of feed, pitch of screen, rate of rotation or oscillation, whether feed is wet or dry, thickness of plate or wire, diameter or size of screening surfaces, shape of opening, etc.

When one desires to determine accurately the quantities of each size in graded materials of granular form by means of sieves, standardized apparatus and methods must be used. In any attempt to standardize sizes of testing sieves, it is important that the effect of the variation of wire diameter with respect to clear opening be known.

A number of different series of sieve sizes have been suggested by various investigators and engineers. Rittinger proposed a geometric series in which the ratio between the size of the clear opening in any sieve in the series to the clear opening of the next smaller sieve was $\sqrt{2}$; the smallest sieve in his series had a clear opening of 1 mm. Other series of fixed ratio between sizes were proposed by J. T. Hoover,[3] Robert H. Richards[4] and others. Sieves conforming to these specifications were not manufactured, however, until about 1910, when the W. S. Tyler Co.[1] developed the Tyler Standard Screen Scale sieves, using the Rittinger ratio from 0.0029-in. opening to 1.050-in. opening.

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[1] Professor, in Charge of Structural Materials Research Laboratory, Lewis Institute, Chicago, Ill.

[2] 1921 Book of A.S.T.M. Standards, p. 751.

[3] J. T. Hoover, "A Standard Series of Screens for Laboratory Testing," *Eng. Min. Journal*, Vol. 90, p. 27 (1910).

[4] Text Book of Ore-Dressing, by Robert H. Richards (McGraw-Hill), First Edition (1909).

The preliminary investigation described in this paper was not concerned with ratio of successive sizes, but rather was undertaken to determine what effect, if any, would be produced by changing the wire size, keeping the clear openings the same.

Tests were also made to compare results obtained by shaking the sieves by hand and by machine for 1, 5 and 15 minutes.

Four groups of four or five sieves each, having approximately the following characteristics, were used:

APPROXIMATE CLEAR OPENING, IN.	RANGE IN RATIO OF WIRE DIAMETER TO CLEAR OPENING
0.185	0.91 to 0.17
0.045	1.37 to 0.22
0.023	1.22 to 0.56
0.0115	1.09 to 0.58

MATERIALS AND TESTS

Eighteen brass-bound woven-wire sieves (not twilled) 8 in. in diameter and 2 in. deep, purchased from the W. S. Tyler Co., Cleveland, were used in the tests. It was impracticable to secure wire cloth of the same metal for all sieves, consequently, steel, brass, bronze, and tinned wire were used indiscriminately. Each group covered as wide a range of ratio of wire diameter to clear opening as seemed practicable without going to extremes.

For machine-sieving, a Ro-Tap sieve shaker running at 145 r.p.m. was used. The machine gives a horizontal motion to the sieves and at the same time produces an impact or tapping effect by means of a hammer which strikes the top of the nest of sieves at regular intervals. Fig. 1 is a general view of the machine. For the hand method the sieves were shaken in such a way as to produce both a horizontal and vertical motion.

Sand from Elgin, Ill., and crushed marble from Tuckahoe, N. Y., were used to test the performance of the sieves. The sand is typical of a granular material containing rounded particles and the crushed marble of one containing angular particles. For each group of tests the same sample was used for the different sets of sieves. That is, after each test, the sample was recovered and used for the next test.

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[1] G. A. Disbro, "Screen Scale Sieves Made to a Fixed Ratio," *Proceedings*, Am. Soc. Testing Mats., Vol. XIII, p. 1053 (1913).

DISCUSSION OF TESTS

The data of the tests are given in Tables I, II and III. In general each value is the average of duplicate determinations on the same sample.

Effect of Wire Diameter.—Table I gives the dimensions of the sieves, as reported by the manufacturer and as measured in the laboratory. A micrometer microscope was used for measuring the diameter of wire and the size of clear opening. The wire diameter was determined by averaging 2 readings each on the warp and woof. The "warp" is the fixed straight wires in the sieve, while the "woof" runs crosswise to the warp and interlaces with it. The diameter of wire as measured by the laboratory checked closely with that given by the manufacturer. Measurements of the sizes of clear opening differed as much as 10 per cent from that given by the manufacturer.

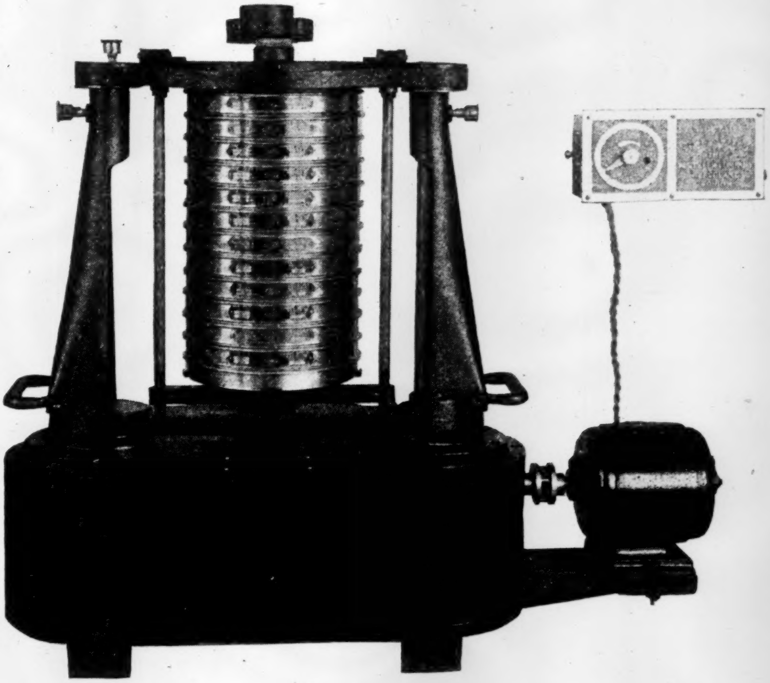

FIG. 1.—General View of Ro-Tap Sieve Shaker.

Table I also gives data showing the effect of diameter of wire on the percentages of sand and marble retained by different sieves having the same clear opening. These tests were made using the Ro-Tap

TABLE I.—DIMENSION OF SIEVES AND TESTS OF SAND AND MARBLE.

8-in. brass-bound sieves, 2 in. deep, manufactured by the W. S. Tyler Co., Cleveland.
Measured dimensions are averages of 4 readings, 2 across the warp and 2 across the woof.
Tests made in Ro-Tap sieve shaker operated for 15 min. at 145 r.p.m., using one sieve at a time.
For each grading the same sample was used for each sieve.

Sieve		Manufacturer's Dimensions			Measured Dimensions			Tests of Sand and Marble		
No.	Wire	Clear Opening, in.	Wire Diameter, in.	Ratio, Diameter to Opening	Clear Opening, in	Wire Diameter, in.	Ratio, Diameter to Opening	Grading of Sample	Per Cent Coarser than Sieve, by Weight	
									Sand	Marble
3	Steel	0.185	0.148	0.80	0.163	0.148	0.91	8 - $\frac{3}{8}$	49	66
$3\frac{1}{2}$	Brass	0.181	0.105	0.58	0.178	0.106	0.59		49	70
4[a]	Brass	0.185	0.065	0.35	0.184	0.067	0.36		49	71
$4\frac{1}{2}$	Tinned	0.187	0.035	0.19	0.204	0.035	0.17		49	65
10	Brass	0.0460	0.054	1.17	0.0399	0.055	1.37	28 - 8	38	36
14[a]	Brass	0.046	0.025	0.54	0.0470	0.025	0.53		37	37
16	Brass	0.0465	0.016	0.34	0.0490	0.016	0.32		37	38
18	Bronze	0.0456	0.010	0.22	0.0446	0.010	0.22		40	42
18	Steel	0.0236	0.32	1.36	0.0255	0.028	1.22	48 - 14	39	61
24	Brass	0.0237	0.18	0.78	0.0245	0.018	0.73		36	61
26	Brass	0.0235	0.15	0.64	0.0247	0.014	0.54		34	59
28[a]	Brass	0.0232	0.125	0.54	0.0222	0.0125	0.56		38	63
30	Brass	0.0233	0.010	0.43	0.0226	0.013	0.56		38	64
40	Brass	0.0115	0.0135	1.18	0.0122	0.013	1.09	0 - 30	82	28
45	Steel	0.0112	0.010	0.89	0.0130	0.010	0.77		82	30
48[a]	Brass	0.0116	0.0092	0.79	0.0114	0.0098	0.86		81	30
50	Brass	0.0120	0.008	0.67	0.0123	0.008	0.64		79	30
55	Tinned	0.0112	0.007	0.62	0.0118	0.007	0.58		80	29

[a] "Standard Screen Scale" sieves.

TABLE II.—EFFECT OF DIAMETER OF WIRE ON THE PERFORMANCE OF SIEVES.
(Using Graded Samples)

Sieves for each set (A, B, C, D) nested and tested together.
The same sample was used for each set.
The Ro-Tap sieve shaker was used. (145 r.p.m.)
Tests on sand and marble each graded 0-$\frac{3}{8}$ in. A complete sieve analysis of each sample is secured by reading across the table.

Sieve Set	Average Clear Opening, 0.185 in.			Average Clear Opening, 0.046 in.			Average Clear Opening, 0.0235 in.			Average Clear Opening, 0.0115 in.		
	Sieve No.	Wire Diameter, in.	Per Cent Retained	Sieve No.	Wire Diameter, in.	Per Cent Retained	Sieve No.	Wire Diameter, in.	Per Cent Retained	Sieve No.	Wire Diameter, in.	Per Cent Retained
					SAND GRADED 0-$\frac{3}{8}$ IN.							
A	3	0.148	10	10	0.054	44	18[b]	0.032	62	40	0.0135	90
B	$3\frac{1}{2}$	0.105	11	14	0.025	45	24	0.018	63	48	0.0092	91
C	4	0.065	11	16	0.016	45	28	0.0125	64	50	0.008	91
D	$4\frac{1}{2}$	0.035	9	18[a]	0.010	46	30	0.010	65	55	0.007	90
					CRUSHED MARBLE GRADED 0-$\frac{3}{8}$ IN.							
A	3	0.148	21	10	0.054	49	18[b]	0.032	77	40	0.0135	88
B	$3\frac{1}{2}$	0.105	22	14	0.025	50	24	0.018	79	48	0.0092	89
C	4	0.065	24	16	0.016	51	28	0.0125	80	50	0.008	89
D	$4\frac{1}{2}$	0.035	22	18[a]	0.010	53	30	0.010	81	55	0.007	8[illegible]

[a] Bronze.
[b] Steel.

operated for 15 minutes at 145 r.p.m. Only one sieve was shaken at a time. Samples of the sand and crushed stone for use in comparing sieves with different sized wire were prepared by passing the material through sieves a size larger than the average nominal sizes under test and using that retained on the next smaller sieve. For example, in testing the sieves with a clear opening of 0.185 in. (Nos. 3, $3\frac{1}{2}$, 4 and $4\frac{1}{2}$) the material was graded between the $\frac{3}{8}$-in. and No. 8 sieves.

The results in Table I show that the diameter of wire had little effect on the amount of material retained on sieves of the same clear opening. For the group having a clear opening of 0.185 in., the amount retained in each sieve was 49 per cent in the case of the sand, and for the crushed marble 66, 70, 71 and 65 per cent were retained on the No. 3, $3\frac{1}{2}$, 4 and $4\frac{1}{2}$ sieves, respectively. No relation was found between these latter percentages and the dimensions of the wire sieves. Similar tests were made using sands and crushed marble samples graded from No. 28 sieve to No. 8, from No. 48 to No. 14, and from 0 to No. 30 with groups of sieves having average clear openings of approximately 0.045, 0.023, and 0.0115 in., respectively, and with wide ranges in wire diameter. The same uniformity in results will be noted for the different sieves in each group.

TABLE III.—EFFECT OF TIME OF SIEVING AND COMPARISON OF MACHINE AND HAND SIEVING.

Four sieves were nested; the test for a given time of sieving was made in one operation.
The same sample for each kind of material was used throughout.
The Ro-Top sieve shaker was used for the machine sieving (145 r.p.m.)

Sieve No.	Wire Diameter, in.	Clear Opening, in.	Machine Sieving. Amounts Retained on Sieve, per cent by weight			Hand Sieving. Amounts Retained on Sieve, per cent by weight		
			1 min.	5 min.	15 min.	1 min.	5 min.	15 min.
SAND								
$4\frac{1}{2}$	0.035	0.187	2	2	1	1	1	0
18[a]	0.010	0.0456	52	51	51	51	50	50
30	0.010	0.0233	72	71	70	72	71	70
55	0.007	0.0112	95	95	94	95	96	95
CRUSHED MARBLE								
$4\frac{1}{2}$	0.035	0.187	21	20	19	20	17	16
18[a]	0.010	0.0456	53	52	51	53	50	49
30	0.010	0.0233	81	80	79	82	79	78
55	0.007	0.0112	89	88	88	90	88	87

[a] Bronze.

Table II gives similar data using graded material. The sieves were shaken by machine, four in a nest. The clear opening of the largest sieve (top sieve) in each nest was approximately 0.185 in.; the smallest 0.0115 in. Sand and crushed marble, each graded from dust to about $\frac{3}{8}$-in. sieves, were used. No attempt was made to secure the same grading for the two materials. Complete sieve analyses for the sizes used will be secured by reading across the table. The four nests of sieves are arranged in the table in ascending order of their wire diameters. The same sample of each material was used for each set of sieves. The greatest range in percentages retained for the four sets of sieves was from 62 to 65 for sand and 77 to 81 for crushed stone. These differences were found for the group of sieves having an average clear opening of about 0.023 in.

While these differences are small and well within the allowable range of experimental error, the percentages retained arrange themselves in inverse order to the wire diameter, indicating for this clear opening a slightly smaller percentage retained on sieves with the larger wires. A similar arrangement of values is found for the group of sieves having an average clear opening of 0.046 in. However, this arrangement may be accidental, as the differences are small, and similar relations are not found for the other tests.

Comparsion of Hand and Machine-Sieving.—The effect of time of sieving and a comparison of machine and hand-sieving are given in Table III. There is little difference in results secured by the two methods.

The time of sieving as between 1 and 15 minutes made little or no difference in the results for the materials tested. Between 1 and 5 minutes the differences in percentages were generally about 1; in one instance as much as 3. Between 5 and 15 minutes the differences in percentages were 1 or 0.

CONCLUDING REMARKS

It should be kept in mind that these tests were made on sieves having clear openings ranging from 0.0115 in. to 0.185 in. (approximately from sieves No. 48 to No. 4), and that the results may not apply to finer sieves or wider ranges of ratio of wire diameter to clear opening.

It is not believed that the results of these tests necessarily apply to the separation of materials on a quantity scale, as the sieving action differs from that encountered in plant operation, and in these tests the question of efficiency was not studied.

HOW SHALL THE BENEFITS OF A.S.T.M. STANDARDIZATION BE SECURED TO THE SMALL USER?

By Thomas H. Wiggin[1]

There is an old proverb about never missing the water till the well runs dry. The writer, after twenty-five years' experience in large organizations purchasing under specification with mill and shop inspection, has missed very keenly the benefits of such thoroughness when trying as a consulting engineer to aid certain small users who had fallen into serious difficulty with material purchased in the open market. At present the typical small user—and he is greatly in the majority in numbers and generally in total consumption—never having enjoyed the blessings of tested material, cheerfully takes a chance with what is offered, sometimes sticking to a brand and sometimes swayed by the "just-as-good" salesman of cheaper material.

When accidents occur there is a flurry—generally temporary—of trying to secure better materials and this is found to be a very up-hill road for the small user. By way of illustration a very few cases will be cited.

A piece of wrought-iron hoisting equipment, purchased some years ago from a firm of good reputation under a simple order calling for first-class material (these orders generally name somebody's "Best"), broke under such circumstances as to cause damage to the extent of about a quarter of a million dollars. Chemical examination showed the article to contain about 0.45 per cent phosphorus. Some other similar equipment was found to contain about 0.40 per cent phosphorus. An interesting series of tests was made, proving that this material was entirely unsuited for hoisting equipment, though curiously enough it withstood rotary endurance tests much better than wrought iron of good chemical composition which exhibited most satisfactory physical properties in tension, bending and impact tests. The chain smith who fabricated the samples from good and bad material pronounced all of it good, but gave some slight preference to the bad material, showing that the opinion of the mechanic is no substitute for the standardized test of technical societies.

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[1] Consulting Engineer, New York City.

Subsequent experience in trying to avoid unsuitable material in new equipment and to get wrought iron approaching U. S. Navy standards developed an inertia and apparent ignorance which was and is perplexing considering the wide membership of this Society. One excellent mill does not make any wrought iron under specifications limiting phosphorus or other ingredients, though the material will generally meet Navy specifications. A prominent firm making rolled material and hoisting equipment does not take orders limiting composition even if permitted to name its own within reasonable limits. More profit in non-specification material is the reason given and is doubtless the truth. Several other firms knew nothing about the chemistry of their product. The field of competition available to a small user for specification wrought iron seems to be very narrow, though the writer's investigation has never been exhaustive.

Another case concerned some rolled steel which developed only about one-fourth of the usual strength under the conditions of service. The material was purchased of a large mill under the same form of non-technical order that had been used for years. After an expensive series of accidents, that threatened the reputation of an important business, the offending material was thoroughly examined and found to be full of slag inclusions, which of course did not show at all except in metallographic examination. Incidentally it contained about three times as much carbon as was generally thought suitable for such material, though examination of previously supplied successful material showed the carbon content to be unimportant up to the limit existing in the material which failed.

Many less important cases of material that could not have passed any standard test, even the mildest, have doubtless come to the attention of most of those who will read this paper. The writer will merely mention two other cases: one, some bolts that proved to be of bushelled material containing a surprising variety of ingredients up to hard tool steel; the other, a cap-screw which twisted off recently like lead, even before coming to a seat, thus resulting in an expensive boring job costing as much as would 200 bolts. In both cases, large reputable firms supplied the goods.

It is obvious, with the keen competition of business and the insistence of purchasers on obtaining the lowest price, that the mass of goods offered to the general purchaser will be below the standards set by this and other similar societies. The presence of inspectors representing large consumers tends to keep products up to a high standard and the small consumer profits thereby, but can seldom be sure. The writer has known goods rejected by large consumers to be shipped to small consumers. In fairness to these unnamed manufacturers the writer will add that in these cases the inspector for the manufacturers used good judgment and apparently did not pass anything that had defects likely to cause failure.

There are doubtless many concerns that are generally rigid in their self inspection, but probably even most of these use their own judgment as to the necessity of some of the stricter limits mentioned in standard specifications, and if it were not so, goods would cost more to the general consumer. Yet it ought to be possible for a consumer to buy small quantities of nearly any kind of material or article that has received the attention of the American Society for Testing Materials and similar societies to the extent of producing standard specifications, with the certainty that the goods fulfilled the specifications. If these standards are impracticably high for general application, then other standard grades which are practicable should be established.

The writer is aware that progress has been made along these lines. For example, steel may be bought on certificate of test provided the order is for over about 50 tons and provided there is time to wait for a rolling. But this is beyond the ordinary small user. Some associations of manufacturers of special products have raised their standards greatly and in some cases marks are affixed meaning guaranteed excellence or composition. The practice aimed at unsuccessfully by advocates of a complete pure food law is paralleled in the case of some firms in the printing of formulas on their labels, notably in the case of paints. Fire and boiler underwriters, also state and national governments, are enforcing regulations which result in mill and factory inspection of certain materials and equipment, such as boiler plate, fire pumps, hose, sprinklers, etc. Even the small user of boilers often gets inspection service of these special agencies.

For practical purposes the direct results for the small consumer are few, though the indirect results of the A.S.T.M. and similar organizations are large in raising general standards and thus increasing the probability of the general consumer receiving satisfactory goods. However, what the writer had in mind in proposing this paper was not merely probability but certainty for the small user in so far as sampling and testing of a given heat or lot of material, such as is practical for the larger user, will yield such certainty.

The writer has only two suggestions, which are in no wise new in their essence, as to methods by which the desired condition may be brought nearer:

1. A more constant recognition and emphasis by members of the A.S.T.M., both producers and consumers, that standards are for general use and not simply for use where there is inspection by the purchaser.

2. The more general adoption of short designations for different grades of material, corresponding with A.S.T.M. standards, and of the practice of stamping goods, after standard tests, with the name of the manufacturer and grade, so that the small user can specify and have proof that he is getting material of the grade which he desires and is willing to pay for.

The last four words of the previous sentence have much to do with the problem and doubtless in part spell the reason for the slow progress. The value of reliable grades is, however, generally recognized in modern manufacture and advertising, and people do often pay for what they hope is the best material. The writer knows from experience, nevertheless, that trade names may be used as a cover for goods of widely different quality and it would be enormously more valuable to the intelligent buyer (and that will mean most buyers as soon as the idea becomes a part of our extremely effective modern advertising) if instead of, or at least in addition to, the trade name there were marked on the goods some A.S.T.M. number meaning standard quality and guaranteed inspection. The fabrication of job lots of goods made as cheaply as possible for competitive trade among the great mass of uninformed retailers and small users would gradually be eliminated, and careful manufacturers as well as the public would be benefited.

As in other fields of propaganda, publicity will help greatly. There is probably a little tendency to inbreeding in societies of our kind that is often overlooked by the able specialists who devote so much effort to the advancement of high technical standards. Perhaps some of our foremost members would be surprised at the ignorance, even among engineers, of the work of the American Society for Testing Materials. It needs blazoning. The Bureau of Standards and the activities of the American Engineering Standards Committee in promoting American standards which will have wider circulation, have aided publicity and will do more in the future. Knowledge of the advantages of using tested material must precede any intelligent demand by the general user to participate in those advantages. The A.S.T.M. should not stop with its high technical success among experts, but should strive definitely to make its work known and more intimately a part of the general welfare.

DISCUSSION

Mr. Speller.

MR. F. N. SPELLER[1] (*presented in written form*).—Regarding this question suggested by Mr. Wiggin's paper, it might be well to consider how the general use of standard specifications has benefited the user where the products purchased under these specifications have been widely distributed among a large number of consumers, large and small.

The U. S. Steamboat Inspection Service has had a specification for boiler tubes which in some respects is essentially equivalent to the A.S.T.M. specifications. No inspection is made by this bureau but the manufacturer is required to issue a sworn statement that his product is made to this standard. This practice has been in use for over twenty years and undoubtedly has helped materially to maintain a good standard in marine tubes.

The A.S.M.E. Boiler Code (containing the A.S.T.M. specifications) is another instance of a somewhat similar system except that no statement is required of the manufacturer, and inspection may be made at the mill. The code has now been adopted as law in eighteen states. The American Petroleum Institute has adopted a specification for tubular goods based on A.S.T.M. specifications, but modified to suit special dimensional requirements in the oil fields. Material purchased under this specification is marked A.P.I. Standard. The more general the use of the A.S.T.M. specifications on the part of other engineering societies and large consumers and manufacturers, the more should the small consumer be benefited indirectly.

It is also of some advantage to manufacturers to make their more important products to one standard, provided this is a reasonable one. A minor portion of the boiler tubes made by our company is inspected under the A.S.M.E. requirements (A.S.T.M. Standard), but we find it of advantage to make *all* tubes to this standard so that the small consumer is able to buy this standard for any purpose.

The variation from standard introduced by some consumers into their specifications is an obstacle to the adoption of a general standard. This is sometimes done after the specification has been accepted by representatives of these interests on the A.S.T.M. committees. When such changes are necessary it would be better if they were added as an appendix and the A.S.T.M. specification accepted with reservation.

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[1] Metallurgical Engineer, National Tube Co., Pittsburgh, Pa.

Mr. Speller. This would make for uniformity, assist the committees having to do with revisions and make inspection much easier.

The main difficulty in the general use of such standards is that so much of the product is distributed through jobbers and agents, and that the small user is unable or unwilling to stand the expense of inspection at the mill. On the other hand it does not seem to be commercially possible for the manufacturer to submit to inspection of his product at destination as a general rule, especially when the product passes through several hands to the small consumer. Some system of general inspection or control at place of manufacture might be worked out for certain products and sponsored by an organization which would be acceptable to both manufacturer and consumer, the manufacturer agreeing to work to the A.S.T.M. standards, which are as a rule acceptable.

After all is said and done, the consumer must depend to a large extent on the reputation of the manufacturer, so that an agreement to make a certain product to the A.S.T.M. standard would seem to be helpful to the small consumer if such an agreement could be worked out in a practical manner

It would seem that the A.S.T.M. should seek or provide some satisfactory means for seeing that their specifications are carried out, or endeavor to have their specifications adopted still further by other organizations which have such power.

Mr. Walker. MR. P. H. WALKER.[1]—The paper under discussion deals with a matter to which I have given a great deal of consideration from a nonpartisan standpoint. There is one method of procedure that it seems to me would offer assistance to the small purchaser if it were carried out by a large number of manufacturers, and that consists in placing on the label the statement that the material does conform to a certain A.S.T.M. specification. Now if that is done and the manufacturers' association tries to see that its members are honest in making the statement, material that goes into interstate commerce can be the cause of prosecution by the Federal Trade Commission if the statement is incorrect. I know that that has been done not specifically in regard to certain specifications, but in regard to the misrepresentation of materials in the paint and varnish industry. I know that a good many manufacturers of shellac varnish, for example, have been reprimanded by the Federal Trade Commission for stating that they were selling pure gum shellac in alchool when they were not selling it, and the same thing would undoubtedly apply if a manufacturer stamped his steel as being in conformity with a certain A.S.T.M. specification and it could be shown that he was selling material that did not conform to that specification. It would be a question then for the reputable manufacturers of that line of goods to take steps to have the guilty ones prosecuted, which would be to the advantage of both the consumer and the reputable manufacturer. **Mr. Walker.**

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[1] Chemist, U. S. Bureau of Standards, Washington, D. C.

MR. J. A. CAPP.[1]—The paper asks a question and it suggests an answer, that is, that the manufacturers themselves undertake to make people want material according to A.S.T.M. specifications. That is what the suggestion amounts to. **Mr. Capp.**

The paper also contains an intimation of another answer, which is just as good a one as that the manufacturers make people want something. Why shouldn't we, ourselves, make more people want our work? Why should not more buyers realize that the way to get what they want is to tell people what they want? A man who makes goods makes them for one purpose, to sell them and to have them stay sold. He does not want to have them come back. He does not want to have them the subject of complaint. He wants to sell the same man more goods when the man wants more. He usually has his ear pretty close to the ground to find out when the man is going to buy and what the man wants when he is going to buy. He is not making a line of goods with the idea that he is going to tell the man, "These are what I make; you can take them or leave them." He is going to make his line of goods in the confident expectation that his reading of the public's wants is about right. The general public, when it buys things, buys *things*, literally things, not specific things. If it is going to buy hoisting chain, it buys chain, and there are all kinds of chain made and probably each of these various kinds has a good use. When it buys castings, it buys just castings. If you go to the average buyer, you will have a hard time convincing him that a casting is not a casting, that there are differences among castings. We have got to make the man who buys goods, then, realize that he ought to want to buy his goods more intelligently than he does, and not just buy goods. He ought to try to find out whether there is a difference among the different sorts and what those differences consist in.

Once enough people intimate to manufacturers that they want to buy goods under A.S.T.M. specifications, the manufacturer is bound to meet that demand. He may not do it by giving you a test result on an individual purchase of one bar of steel, but he will do it by telling you that that particular bar came from a stock of steel which, before he put it in stock, he tested himself according to the method specified in your standard specifications. I happen to come from a pretty

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Mr. Capp. large consumer. We have our own specifications which, to the greatest extent possible, we base on A.S.T.M. standards. We buy small lots of steel where we cannot expect the mill to roll it and test it as they would a big lot. We have not had any particular trouble getting the mill to tell us that the heat was tested before it went into stock, and we have a reasonable assurance that the material would meet all the specifications if it were tested individually. If enough of us do that, big and little buyers alike, we can always have that assurance without any trouble.

Some mention has been made of the general ignorance concerning the American Society for Testing Materials on the part of people who ought not to be ignorant of it. That is a fact and it is a deplorable fact. I happened to talk with some students in a department of a very large university which I will not mention by name. They were taking one of the business courses and had come to a stage in that course where purchasing methods and the like were under discussion. These students, to supplement the classroom work, were sent out to different industries to learn what they could by inquiry during the day or two that they might spend in the purchasing agent's office of a particular plant. Three of them came to me; they had been to our purchasing agent who told them that the question of specifications was settled for him by the laboratory. They came to the laboratory and wanted to know how we made specifications, and, in fact, discussed the question as it had been discussed for them by their professors. They had never heard of the American Society for Testing Materials. The professor had not told them and they had no other way of learning of it. Apparently, the professor had not even told them that there were available standard specifications of any kind whatever; he had simply told them that every concern had to make its own specifications and that they ought to do the best they could to find out on what to base them, what information to get and the like. Our own colleges, which ought to be concerned in the matter, do not seem to be teaching the men what they ought to teach them. In that case, I talked to those particular students about the A.S.T.M. and asked them if they did not think it was a wise thing to use such standards. They were intelligent young men and naturally did think so. I afterward had the opportunity to get in touch with the professor. I do not know whether he agreed with me or not; I rather have my doubts whether he yet thinks it is a wise thing for him in his courses to suggest to his students that if they ever want to talk about specifications for purchasing, they consider the advisability of using A.S.T.M. standard specifications.

There are two things we have to educate, I believe, the buying

Mr. Capp.

public and the educators. You do not need to educate the manufacturers; they will take care of themselves. Once they find a demand, they will meet it, but we have to create it. We have to educate the buyer, and one of the best ways of educating the buyer is to get at him when he is young. Let us do more of our work in the colleges than we have done before.

Mr. Brown

MR. A. L. BROWN.[1]—Good advice has already been given in the statement that purchasers should be influenced to demand standardized articles. The speaker is associated with one of the insurance underwriters mentioned by the author of the paper under discussion and believes that very good results have been obtained in making available for small users the high grade devices needed for fire protection. In this branch of its activities the position of the insurance company is similar to that of an association of purchasers, inasmuch as it represents a large number of users, both large and small, who follow its recommendations closely. Because of this influence, manufacturers have apparently been very willing to conform to specifications which have been drawn up by insurance companies, and they would probably be equally willing to do this in the case of other bodies which are able to provide a sure market. At the present time there are many associations of users, some of which employ engineering ability to prepare specifications and to make tests upon material which they require, and it would undoubtedly assist in securing the benefits of standardization to small users if these associations were made thoroughly familiar with the activities of this Society.

Secretary-Treasurer.

THE SECRETARY-TREASURER.—As pertinent to this discussion, it is of interest to state that arrangements have recently been completed whereby the National Association of Purchasing Agents may sell the standards of the Society to any members of their association at our usual reduced rates to members, by virtue of the membership of the National Association in the Society. When fully developed, this should help materially in acquainting the buyer with A.S.T.M. Standards.

Mr. Shuman.

MR. J. J. SHUMAN.[2]—I think Mr. Capp, with his usual perspicacity, has touched on the very heart of this thing in saying that manufacturers are sensitive to the demand that comes even from the small consumer; so the thing comes right back to what Mr. Wiggin has said in the first place, the small consumer himself must be educated to ask for something definite. Just as soon as a few of them demand A.S.T.M. specifications material, they will get it. The warehouses on which they necessarily depend for most of their supplies will notice such demands and usually will arrange accordingly.

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[1] Steel Inspector, Hydro-Electric Power Commission of Ontario, Toronto, Ontario, Canada.

[2] Inspecting Engineer, Jones and Laughlin Steel Co., Pittsburgh, Pa.

Mr. Shuman. Look what has happened in screw steel. There is no material better standardized than bessemer screw steel to-day, and it was the American Society for Testing Materials that did it. It did it through a series of experimentations that lasted through years and cost a lot of money, but it was done in a scientific way and forever. The small consumer has already profited by what was done in standardizing screw steel, bessemer and open-hearth, cold-drawn and hot-rolled, and wherever he goes for screw steel he will get A.S.T.M. grade even without asking for it; but to make sure, the consumer should insist on A.S.T.M. quality.

In my work I am impressed with this, that too often the small consumer has hurt his own interests by trying to do something original and individual. He forgets that standardization is going on and has made good progress. It is high time that this thing of having to show individuality in writing quality specifications or specifications for workmanship be dropped, and that consumers, large and small, look to it that they buy standardized materials.

Secretary Hoover has the right idea; he is demanding that people get together and standardize. He, with his wisdom in engineering matters, has seen that it means the advancement of American industry beyond that of any other country if we can only standardize. Therefore in our work we are at all times trying to view the specifications that come to us from the standpoint of standardization, and to encourage as much as we can the small consumer and the large consumer to adopt the standards that are now the recognized standards in this country, which in steel products are in almost all cases the A.S.T.M standards.

Mr. Lynch. MR. T. D. LYNCH.[1]—A few months ago, under the question of the value to the Westinghouse Company of specifications, etc., I was asked, "What is the use of them? Can the expense of preparing these different specifications be justified?" In answer to which were given eight advantages and five disadvantages as follows:

Advantages:

1. Uniformity of material;
2. All suppliers bid on the same quality;
3. No misunderstanding of what is wanted;
4. Uniform methods of sampling and testing;
5. Knowledge of material, an aid to design and an aid to standardization;
6. Allows lower grade of material because quality is more uniform and is known;

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[1] Manager, Materials and Process Engineering Department, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

Mr. Lynch.

7. Allows lower factor of safety in design because of uniformity;
8. Reduces the work of the buyer by avoiding the necessity of writing specifications for each order, which specifications might often be insufficient and may be different for different orders.

Disadvantages:

1. Possible higher price due to unnecessarily rigid requirements;
2. Limited market where suppliers refuse to accept specifications;
3. May limit the market where a supplier is ignorant of the quality of his product;
4. Cost of preparing specifications for use in buying;
5. Cost of inspection.

This seems to cover the situation pretty well, not only for a large consumer but for smaller consumers as well, and it also indicates the importance of inspecting material or purchasing it only from thoroughly reliable producers who have produced material of the grade wanted, who inspect their own material and who will stand back of their product with a worthy reputation.

It may be necessary at times to purchase material from manufacturers or from sales agencies who are entering a new field of activity, unfamiliar with the quality of their material and unfamiliar with the use to which it is to be applied. Very great care is necessary in such cases to make sure that the specifications, whether standard or special, are clear and concise and that complete inspection is made, especially on the early shipments.

It is always preferable to use standard specifications wherever possible, since a specification does not become a standard until an agreement between producers and consumers has been reached. Such an agreement automatically guarantees a knowledge of the material by both producer and consumer.

It has been our experience that commercial grades of material purchased on standard specifications come to us very regular in quality and require only supervising or periodical inspection, whereas special materials or those that have not been standardized are much more likely to vary in quality and therefore require much more rigid inspection and corresponding rejections.

Commercial inspection bureaus are available for those who do not have their own inspection department and, in fact, can often be utilized by both large and small consumer to good advantage.

Mr. Lynch. So much benefit has come from the use of specifications on which to purchase material and especially the A.S.T.M. specifications, that it is very desirable, timely, and helpful to extend their use.

Extensive work has been done by A.S.T.M. members through its committees in developing and establishing these specifications. They are now recognized as commercial standards and it is quite proper that their great value should be made known and their use rapidly extended.

The ideas brought out by Mr. Wiggin are timely and I would like to see the specifications developed by this Society made use of by its own membership and thus standardize, commercialize and advertise.

Mr. Arnott. MR. DAVID ARNOTT.[1]—As representing the American Bureau of Shipping I was naturally very much interested to read this particular paper, which deals with a subject of increasing importance to users and manufacturers of all steel products. Gentlemen who have previously spoken have suggested various and useful means of popularizing the work of the American Society for Testing Materials among small users, but I personally feel that one of the first things to do is to get rid of the existing multiplicity of specifications which must be a nuisance to manufacturers. The differences, for example, between the various structural steel specifications are not of vital importance, in some cases between tweedledum and tweedledee, and as we probably get the same material in the end it seems that we ought to have in this country one standard specification for structural mild steel suitable for all ordinary purposes. Our Society is in the unique position of being truly representative of all the various interests concerned. The Society has the necessary talent and influence behind it so that every effort should be made to cut down the number of specifications to a minimum and to have those specifications generally recognized as American standards.

We are all interested in the work of the A.S.T.M., but with most of us it is a particular rather than a general interest. For example, the foundry people who are essentially interested in steel castings probably do not concern themselves very much with regard to specifications for steel plates, although they may have ideas which are worthy of consideration. I think the interests of the manufacturers on the one hand and the consumers on the other can safely be left to our committees, whose members are sufficiently disinterested to hold the balance even, although to do so effectively we must all take an intelligent interest in the work of the various sub-committees. I do not want to take up the time of the meeting but it does appear to me,

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[1] Deputy Chief Surveyor American Bureau of Shipping, New York City.

Mr. Arnott coming right down to fundamentals, that the real way to popularize the A.S.T.M. specifications is for the members individually and collectively to take a keener interest in the work of the Society and make its advantages better and more generally known.

Mr. Rys. MR. C. F. W. RYS[1] (*by letter*).—In attempting to answer the question asked in the title of Mr. Wiggin's paper, it is assumed that by "small user" is meant the man who is manufacturing, and solely responsible for the quality of, some proprietary article which he sells directly to his particular trade. Ordinarily such user's experience is generally limited to the actual manufacturing as carried out in his shop, and he possesses no practical knowledge of how the material in question is manufactured and how its properties may be varied. His selection is consequently more or less haphazard, or is based on tradition, or what has been followed by somebody else no better qualified than himself.

Roughly, the articles manufactured will be those which either:

1. Depend on shape, appearance, or finish without any necessity for paying attention to strength; or
2. Require strength to resist the given service conditions.

In the first case the only requirements of the material are that it shall lend itself readily to forming, shaping, machining and fabricating. In the second case definite properties in the material itself are essential, but even more so in a high proportion in the design.

In either case the first step should be to determine exactly what material is necessary as the result of experiments and intelligent cooperation with the manufacturers and, in certain cases, with competent consulting engineers.

The various A.S.T.M. specifications have been drawn up to cover a wide variety of products and the field is being constantly extended. It is rarely possible, except in a general way, to indicate the enormous variety of products for which they are respectively suitable; and as their number is considerable and in some cases the differences are slight, it is easy to understand how a user without technical training may pass them up in despair. This situation, however, as just pointed out, is readily corrected by consulting the proper authority.

Most of the large manufacturers have adopted A.S.T.M. specifications for their regular practice, or consider them as equivalent to their own standards as far as price and delivery are concerned.

The large jobbers, at least, purchase their stock to definite specifications and can therefore furnish their customers with copies of test reports or other information indicating the quality and properties of the material in question.

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[1] Metallurgical Engineer, Carnegie Steel Co., Pittsburgh, Pa.

Mr. Rys. Again, many orders are received, not necessarily from the small user, which are extremely indefinite, simply calling for "soft steel," "machinery steel," "welding steel," etc. If the manufacturer is thoroughly familiar with the requirements of the user, preferably by a personal conference, he is in a position either to determine at once the proper grade, or else to suggest certain varieties which should be tried out to determine the most suitable, after which the user will be informed what specification number or other instructions should be shown on his subsequent orders. I know of many cases where the user has been purchasing the same grade for a good many years, with the natural assumption on the part of the manufacturer that it was entirely satisfactory, and then a visit or some chance remark has given the manufacturer such information as enabled him to suggest a change which, while usually of small consequence to himself, meant a very great deal to his customer.

Messrs. Beyer and Krefeld. Messrs. A. H. BEYER[1] and W. J. KREFELD[2] (*by letter*).—Enormous strides have been made in the technique and standardization of structural and machine design, all tending toward a more economic use of the materials of engineering. Yet the full benefit of all of this standardization, both of design and of materials, cannot be realized unless the small user as well as the large one can obtain structural materials of the definite physical or chemical specifications called for in the design.

Many of the more important structural materials, such as structural shapes, reinforcing rods, plate steels, cast iron and steel castings, can generally be obtained both in large or small quantities in accordance with standard specifications. One important product of which this is not true to-day is transmission shafting. A committee of the American Society of Mechanical Engineers, in endeavoring to standardize the formulas of design for transmission shafting, found it difficult to recommend definite unit working stresses for use in these formulas, because there appeared to be no standard shafting material available to the average consumer. Transmission shafts are usually purchased in the open market under the trade name of "commercial shafting" and without any definite specifications as to physical or chemical properties. This "commercial shafting" may be either open-hearth or bessemer low-carbon steel, finished by cold rolling, turning and grinding. Its ultimate tensile strength may range from about 45,000 lb. per sq. in. for hot-rolled and turned low-carbon steel to upwards of 75,000 lb. per sq. in. for cold-finished low-carbon steel. The corresponding stresses at the elastic limit would be about 22,500

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[1] Assistant Professor of Civil Engineering, Columbia University, New York City.

[2] Testing Laboratories, Columbia University, New York City.

Messrs. Beyer and Krefeld.

and 55,000 lb. per sq. in., respectively. All grades of steel between these limits are likely to be found in any commercial lot of shafting. It is therefore evident that where risk of failure in a shaft is a serious matter, the working stresses to be used in the design must be based upon the lowest strength of steel likely to be found in any lot of commercial shafting, which to say the least tends toward an uneconomic use of an important engineering material.

In our opinion, it is only a question of time when the engineering profession will more generally recognize this fact and the user will insist upon being able to obtain in the open market, both direct from the manufacturer and the jobber, a standardized shafting material. Such a condition will be quickly brought about when it is more generally known that it will result in many cases in at least a twenty per cent reduction in the cost of transmission shafting installations.

We therefore heartily concur with Mr. Wiggin in his conclusions that there is a real need in the general market for goods stamped with the manufacturer's mark and grade of material. If such a practice is generally established, it will not only result in a more economic use of engineering materials, but safeguard the user against the occasional failure resulting from materials of inferior or unsuitable quality which at present are likely to be found in any commercial lot.

Mr. Wiggin.

MR. T. H. WIGGIN (*Author's closure*).—The author is gratified with the constructive nature of the discussions which the paper has called forth. The suggestions both in the paper and in the discussions are summarized below.

Suggestions in the Paper:

1. More constant recognition by members of the A.S.T.M., both producers and consumers, that the standards are for general use, not simply for use where there is inspection by the purchaser. If a sort of guild feeling or pride could be built up the battle would be nearly won.
2. Adoption of short designations for A.S.T.M. grades and of the practice of stamping goods with appropriate labels indicating that they have been made and tested according to designated grades.
3. Publicity for A.S.T.M. work among consumers and even among engineers.

Additional Suggestions Contained in Discussions:

4. (By Mr. Walker) Elaboration of (2) with respect to making associations of manufacturers responsible for honest labelling and calling attention to the jurisdiction of the

Mr. Wiggin.

Federal Trade Commission in case of fraudulent labels and to the benefits to be derived by reliable producers.

5. (By Mr. Capp) Education of college students in knowledge of the work of A.S.T.M. and similar organizations. Examples of surprising ignorance given.
6. (By Mr. Brown) Propaganda by the Society among associations of consumers which collectively employ engineering advice as to purchasing—insurance associations for example.
7. (By Mr. Shumann and Mr. Arnott) Elimination of as many standards as practicable, following the suggestions of Mr. Hoover.
8. (By Secretary Warwick) Aiding associations of purchasing agents in securing specifications of the A.S.T.M. and at the reduced prices allowed to members. This has already been done in the case of the National Association of Purchasing Agents. The interest of this large body of purchasing agents has great possibility in developing both demand for specification goods and machinery for carrying out the labelling, etc.
9. (A clarifying thought by a member orally to the author) Even large consumers are small consumers with respect to materials not entering into their principal business. By way of illustration, the statement was made that the member's company had more difficulty in purchasing a few gallons of paint, oil or some such material than in purchasing its large quantities of stock material.

Emphasis is put on different ones of the above suggestions in the different discussions but the dominant note is the necessity of educating consumers. Inferentially there is unanimity of opinion as to the main thesis that the Society should not seek academic perfection alone but should go out and make its accumulated learning more definitely useful to small as well as to large consumers.

The author believes that consumers can be and will be educated to demand goods fulfilling standard specifications but he also believes that advertising by producers has created the demand for most brands or styles of goods in common use and could likewise be the greatest factor in spreading knowledge and creating demand for goods fulfilling recognized technical specifications; and further that producers who proceed along these lines will secure advantage in sales over those who do not.

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